Integrating Economics and Ecology: A Systems Approach to Sustainability in the Auckland Region

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Abstract

Urban sustainability has emerged as a central environmental and urban policy issue over the last decade, as our world becomes more urbanised. The purpose of this thesis is to operationalise systems modelling approaches (static, system dynamics) that will lead to improved understanding of urban sustainability in the Auckland Region.

The first part of the thesis critically reviews and synthesises both the *sustainability* and *urban development* literatures. Consideration of the sustainability literature focuses on the economic, ecological, and thermodynamic interpretations of the sustainability concept, leading to the identification of eight principles used to guide the modelling process. The urban development literature revealed a significant schism between the anthropocentric approach of the social sciences and the more biophysical approach of the ecological sciences. Some suggestions are made on how to resolve this impasse.

The static systems (input-output) analysis provided much *structural detail* about the Auckland Region economic system and its environmental system; more importantly, it also details the interdependencies between these systems. A significant achievement was the construction of a 48 industry physical (mass flows) input-output model of the Auckland Region economy, and how the economy depends on physical flows *to and from* the environmental system. This dependency of the economic system on natural capital and ecological services was further illustrated by an input-output analysis showing how the Auckland Region economy appropriates ecological services *within* the Auckland Region. This was supported by an ecological footprinting analysis that revealed how the Auckland Region economy depends on natural capital (land) from *outside* the Auckland Region economy.

The system dynamics modelling extends the static systems analysis, to build the Auckland Region Dynamic Ecological-Economic Model (ARDEEM). This dynamic model is designed to simulate future development pathways for Auckland Region; consequently it contains a number of interconnected modules that represent components critical for achieving urban sustainability in Auckland Region: population, labour force, growth driver (based on an adjusted form of Solow growth theory), economy (financial flows), economy (physical flows), and the economy-environment interface (physical flows). The ARDEEM model's use is illustrated by generating 3 scenarios for the future development of Auckland Region: 'Business as Usual', 'Cornucopian Growth' and 'Prudent Pessimism'.

Finally, several areas for future research are discussed. These should try to develop further the theory that underpins urban sustainability modelling, particularly regarding improved integration of disparate theories. The best prospects lie in the future development of ARDEEM, incorporating more sectoral detail (20 – 30 industries), spatial dynamics and ecological processes that were not originally included primarily due to the lack of data.

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Chapter One

Introduction

1.1 Issues of Growth in the Auckland Region

New Zealand is one of the most urbanised countries in the world, with more than 85 percent of its population living in urban areas. Since the 1950s New Zealand's cities have grown rapidly outwards at relatively low densities (Ministry for the Environment, 2000). The pattern of urban growth has paralleled that of most developed nations. A key feature has been the development of cities geared toward transportation; road, rail, water and air networks have all strongly influenced the shape, form and density of our cities (Perkins *et al.*, 1993). In Auckland Region, urban growth has largely been unconstrained with sprawl encroaching on the surrounding rural hinterland.

The Auckland Region measures approximately 120 kilometres from north to south and spans 60 kilometres at its widest. With a land area of just 5,600 square kilometres, the region makes up only 2.0 percent of New Zealand's land area, but is densely populated with 29.5 percent of New Zealanders living there. The Auckland Region is made up of seven territorial local authorities (TLAs) – three districts (Rodney, Papakura and part of Franklin) and four cities (North Shore, Waitakere, Auckland and Manukau). Auckland Region is the largest and fastest growing region in New Zealand with a population of 1.23 million at the 2001 census. The population is projected to grow to 1,793,300 in 2026, a nearly 50 percent increase between 2001 and 2026. This means that the Auckland Region is growing roughly by the population equivalent of a city the size of Dunedin (as at census 2001) every five years. Five of Auckland Region's seven TLAs are predicted to be in the ten fastest growing TLAs nationwide over the next 25 years.

Growth in the Auckland Region escalated in the mid 1960s, partly as a response to post-World War II growth in manufacturing. This, together with an expansion in jobs and population, led to a concentration of industry in the Region and a preference by business to locate there. Ethnic diversity resulting from post-war migration of Maori and Polynesians to the Auckland Region as labour for the manufacturing sector, and more recently, encouragement by government of business migrants particularly from Asia, has made the Auckland Region relatively distinct from other regions in New Zealand. Population growth within the region and its main cities has continued to escalate, and attempts to limit the Region's growth and prevent urban sprawl have been largely unsuccessful.

Urban sprawl, coupled with increasing affluence, has led to significant pressures being placed on the biophysical environment (Newman, 1999); examples include increased per capita demand for natural resources like land, water and energy, and increased assimilative demands on ecosystem services like CO_2 absorption, biodegrading of waste, and cleansing of pollutants by fresh water systems and the ocean. A wider definition of environment also encapsulates losses of culture and heritage, pressures on amenity values, and adverse effects on wellbeing and health of people and communities. Furthermore, these impacts are not necessarily localised, but may be felt well beyond municipal limits, i.e. the appropriation of carrying capacity.

Although its population is relatively modest in global terms, the Auckland Region urban area far exceeds that of most international cities. With the rapid increase in motor vehicle use in the 1950s and the introduction of motorways, the urban area expanded outward and congestion became a concern. Urban sprawl has meant Aucklanders depend heavily cars; as at the 1996 census, 14.1 percent of households owned three or more vehicles compared with 11.1 percent nationally. Traffic volume in the region is the greatest in the country; more than double that of the next closest region of Waikato, with travel to work being the primary generator of traffic flows. The problems caused by growth are also revealed in other areas e.g. water sewage and electricity services, which are all vulnerable and require substantial investment.

With its rapidly growing population, environmental issues are critical to the Region. A growing population accompanied by significantly more economic throughput means more resource use and more waste generation. For example, Auckland Region's escalating traffic congestion results in increasing CO_2 emissions. The Auckland Regional Council (1998, p.2), in its *Draft Annual Plan 1997/98*, states its role is to "protect the region's air, soil and water resources from pollution and to ensure their sustainable use as Auckland develops". To promote these goals, the Regional Growth Forum, comprising representatives of the local councils, has been established. The role of the Regional Growth Forum is to "develop sustainable growth strategies to accommodate anticipated population growth while maintaining and improving the quality of life of Aucklanders" (Statistics New Zealand, 1999, p.3).

The distribution of the labour force reveals Auckland Region's commercial dominance. Auckland Region's status as an international market is reflected in the relatively high proportion of people employed in the wholesale trade industry (1996 census): 9.0 percent compared with 6.2 percent nationally (Statistics New Zealand, 1999). Service industries such as finance, insurance, property services and business services also employ a larger share of the population, with legislators, administrators and managers accounting for 14.9 percent of all employed people in the region, compared with 12.2 percent nationally (Statistics New Zealand, 1999).

These occupations reflect the size of the urban area and the high number of company head offices found in the region. Not surprisingly, employment in the agriculture, forestry and fishing industries was about one-quarter of the national percentage, reflecting Auckland Region's predominantly urban nature (Statistics New Zealand, 1999). Growth of the tertiary sector rather than the primary or secondary sectors means that resource use per capita will be lower in the Auckland Region; however, this is offset by population growth which requires increasing resource inputs and produces more residual outputs.

1.2 Need for a Systems Approach to Urban Sustainability

Urban areas such as the Auckland Region provide significant challenges for sustainable development due to the highly modified nature of the urban ecosystem; a facet of population density, intensive resource depletion and environmental degradation, and conflict between people/communities and their environmental, economic, social and cultural requirements (Parliamentary Commissioner for the Environment, 1998). Urban sustainability involves integrating the requirements of environmental management, social equity and economic opportunity into decision making. This is a process of change in which the use of resources; generation of wastes, emissions and pollutants; and technology and institutional factors are managed to meet the needs of current and future generations.

Despite recognition of the importance of urban sustainability and the need to adopt an integrated perspective on this issue the literature is devoid of substantive theory and method that give greater weight to the definition of urban sustainability (Slocombe, 1993). Therefore, a challenge for this thesis is to develop a theoretical framework and associated analytical tools to give operational meaning to the concept, as it is applied to the Auckland Region. Without such endeavours, the concept of urban sustainability will remain abstract and elusive, and decision makers and communities will be unable to make informed choices about the trade-offs inherent in the concept.

There is widespread appreciation that urban sustainability can only be adequately dealt with through an integrated perspective that encapsulates the whole spectrum of economic, social and ecological values. Without such a perspective, robust and enduring solutions to the urban sustainability problem will remain elusive.

Systems theory and modelling are used in this thesis as one way of addressing the need for an integrated perspective. Because of the complex nature of urban sustainability, the traditional scientific method (reductionism) is not suitable. Instead, a systems methodology, which is concerned with the functioning of the whole rather than the individual parts, is more suitable. This systems methodology has been developed over the last 40 years, gaining wider acceptance in the scientific community (Forrester, 1978; Checkland, 1981, Meadows *et al.*, 1992).

More specifically, systems modelling methods (static and dynamic) are applied in this thesis to address the issue of urban sustainability. Methods like system dynamics which is used in this thesis, attempt to model complex systems that are characterised by feedbacks, non-linearities, time lags and at a higher level emergent properties (Costanza and Voinov, 2004). System dynamics can be used to project future scenarios for Auckland Region, providing stakeholders with better information on the trade-offs and interconnections of the economic, social and ecological dimensions of urban sustainability.

1.3 Research Aims and Objectives

1.3.1 Overall Aim

The overall thesis aim is to develop an operational systems modelling approach to address the issue of urban sustainability in Auckland Region.

1.3.2 Specific Objectives

Specific objectives for this PhD project are to:

(1) Provide a theoretical interpretation of the concept of urban sustainability by drawing upon the relevant literature from the social and biophysical sciences. From this analysis, to develop a set of principles for determining urban sustainability that can be used in the systems modelling.

(2) Extend and further develop static modelling methods (input-output analysis) that have previously been used to understand economy-environment interactions but have not been widely used to understand urban sustainability. Such methods define the structural relationships in complex urban areas between the economy and the environment.

(3) Develop an analytical framework for understanding urban *dynamics* and *changes* in urban sustainability in Auckland Region, drawing on theories of economic growth, spatial change, urban development and urban economics.

(4) Develop a dynamic simulation model of key interactions between population change, socio-economic trends and ecological flows (resources and residuals) in Auckland Region, then utilise this dynamic simulation model and associated indicators to project alternative scenarios of sustainable (or unsustainable) economic and social change in the Auckland Region.

1.4 Methodological Approach

The methodology used in this thesis consists of four integrated components:

(1) Critical reviews and synthesis of the relevant literature that relate to different dimensions of urban sustainability and change: (i) economic, ecological and thermodynamic interpretations of the sustainability concept; (ii) theories of urban change including those from urban ecology, urban geography, urban psychology, urban political economy, urban metabolism and ecological footprinting; and (iii) growth theories including neoclassical growth theories, endogenous or new growth theory, amongst others. The purpose of these literature reviews and syntheses is to provide a firm theoretical basis for systems modelling of the urban sustainability concept undertaken later in the thesis.

(2) Development of a clear and conceptual framework for analysing urban sustainability in Auckland Region. Before the systems modelling can proceed, the different dimensions of urban sustainability in Auckland Region need to be conceptualised in an integrative fashion. A particular focus of this thesis is the interconnection between the economic system and the environmental system. The dynamics of both systems need to be understood as a basis for the systems modelling. A key challenge is to integrate the different perspectives on the issue of urban growth and change that became evident from the critical synthesis.

(3) Development of Static Models of the economic and environmental systems as well as the interconnections between each system. These static (input-output) models provide detail on the structural interdependencies within and between the systems. There are several other reasons for building static models of the Auckland Region economy-environment: (i) determining the state of these systems; (ii) setting the initial conditions for the dynamic models; (iii) to undertake comparative statics analysis; and (iv) analytical ease which allows for wider use and accountability of such models for end-users.

(4) Development of Dynamic Models of the economic and environmental systems, as well as the interconnections between each system. A significant limitation of many models is that they are static, i.e. they only represent a snapshot of reality at a single moment. Reality, however, is not static, but constantly changing. In this thesis, a dynamic model (ARDEEM) is built of the Auckland Region economy and its interaction with the environment system using the system dynamics modelling approach. This system dynamics model is used to model future scenarios of economic and environmental change in Auckland Region, developing the earlier work of Ryan (1995) who built such models for New Zealand. As an adjunct (Appendix B) to this thesis, a model of ecological processes in the global environment system was operationalised. However, such a model proved too difficult to operationalise for the Auckland Region, primarily due to the lack of data.

1.5 Thesis Organisation

This thesis is divided into three distinct yet related parts:

Part I Theoretical Frameworks: How Do Regions Develop and Grow Sustainably

Part II Environment-Economy Interactions in Auckland Region:
A Static Systems Analysis

Part III Environment-Economy Interactions in Auckland Region:
A Dynamic Systems Analysis

The interrelationships between these different parts of the thesis and the constituent Chapters are described by Figure 1.1.

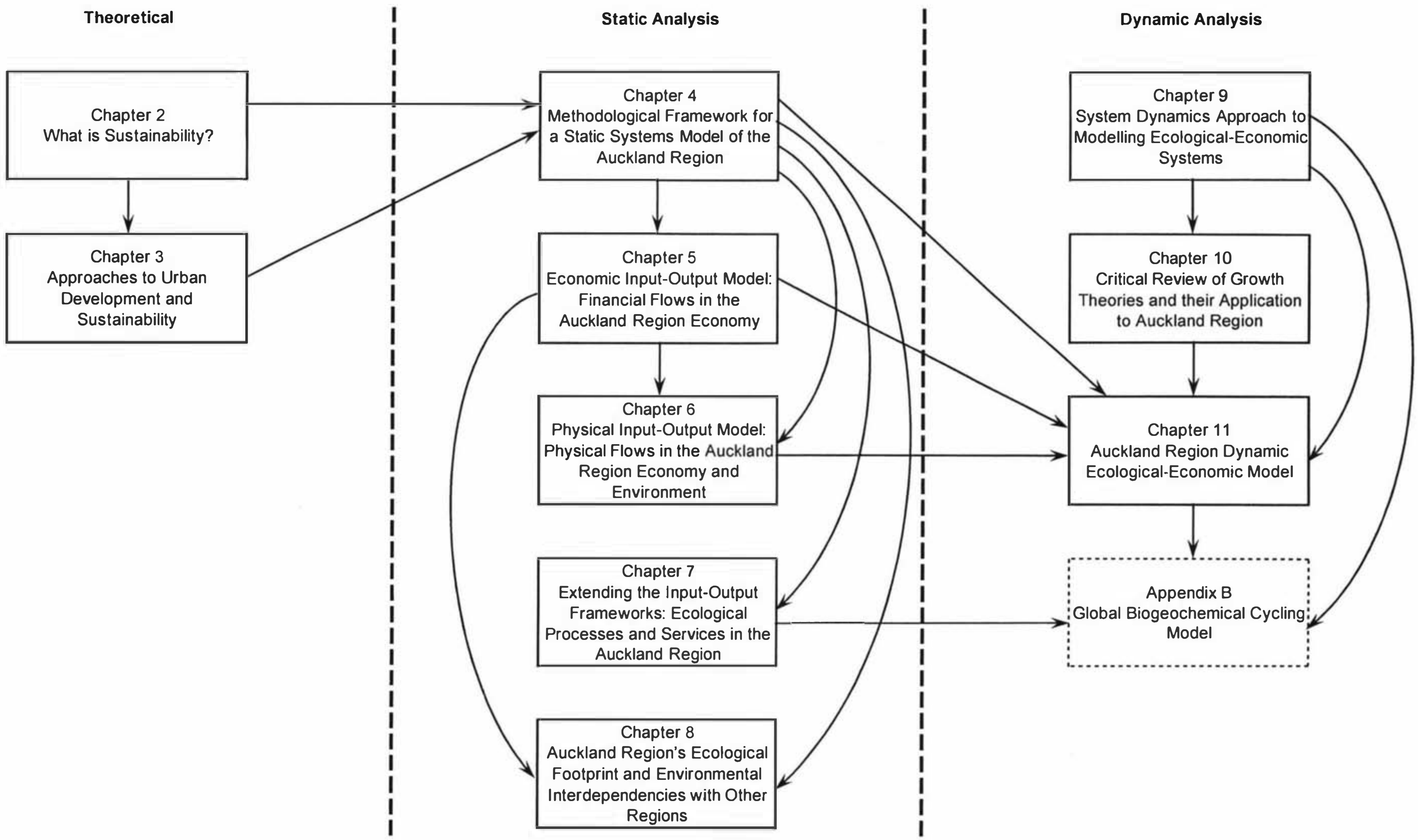

Figure 1.1 **Interrelationships between Thesis Chapters.** Note: Appendix B is dashed as it is a global, rather than Auckland Region specific, model.

Part I (Theoretical) addresses the research questions of sustainability and growth in urban centres through a theoretical analysis of the literature. Chapter 2 reviews the sustainability literature to examine the economic, ecological and thermodynamic interpretations of sustainability. Chapter 3 then turns to the issue of urban growth and sustainability, as viewed through various disciplinary perspectives in both the social and biophysical sciences.

Part II (Static Modelling) analyses the structural interdependencies within and between the Auckland Region economic and environment systems. Chapter 4 provides a conceptual and related mathematical framework for Part II. Chapter 5 builds an economic input-output model of the Auckland Region economy and undertakes various analyses of the structure of this system. Chapter 6 builds a Physical Input-Output model of the Auckland Region economy that qualifies the flows of mass through the economy, as well as between the economy and environment. This Physical Input-Output model is important for understanding the biophysical and ecological aspects of urban sustainability, and represents a first attempt to operationalise such a model at the regional level. Chapter 7 extends the static (input-output) modelling framework to cover ecological processes and ecosystem services in the environment system. Some attempt is made to determine how these ecological processes and services support economic activity in the later part of Chapter 7. Chapter 8 uses ecological footprinting analysis to highlight the fact that urban areas such as Auckland Region depend on natural capital and ecosystem services drawn from other regions. In Auckland Region's case this is very significant, given its small natural capital base and hence its unavoidable dependence on other regions.

Part III (Dynamic Modelling) builds on the static analysis to dynamically model the Auckland Region economy and its interaction with the environment. Chapter 9 delineates the key features of the system dynamics approach to modelling and its methodological underpinnings. Chapter 10 critically reviews growth theories and their possible application to the Auckland Region model. This review is important as it informs the selection of a growth driver in the dynamic model of the Auckland Region economy. Chapter 11 develops a dynamic model of the Auckland Region economy and its interactions with the environment system. This model contains several interrelated modules: population, labour force, growth (based on growth theory), economic, economic physical flow and an economic-environment physical flow. This model is used to produce data for three scenarios for Auckland Region: Scenario 1 'Business-As-Usual', Scenario 2 'Cornucopian Growth', and Scenario 3 'Prudent Pessimism'. To conclude, Appendix B presents a dynamic global biogeochemical cycling model.[1]

[1] This model is a novel by-product of the thesis.

PART I THEORETICAL FRAMEWORKS

HOW DO REGIONS DEVELOP AND GROW SUSTAINABLY?

Chapter Two

What is Sustainability?

The term *sustainability* is a popular buzzword of academic theory and public policy concerned with the environment. According to Caldwell (1990), the concept of sustainability was first acknowledged at the international policy level at the 1972 United Nations Conference on the Human Environment. The term has since gained greater international political importance in publications such as *World Conservation Strategy* (IUCN, 1980), *Our Common Future* (WCED, 1987), *Caring for the Earth: A Strategy for Sustainable Living* (IUCN, 1991), *Rio Earth Summit Conference on Environment and Development* (UNCED, 1992), *Kyoto Protocol to the United Nations Framework Convention on Climate Change* (UNFCCC, 1997), and the Johannesburg Conference *Report of the World Summit on Sustainable Development* (United Nations, 2002).[2] Nevertheless, it was the WCED (1987, p.43) report that popularised the notion of sustainable development, defining it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Sustainability has however been criticised as vague, unrealistic, contradictory, and politically expedient. Dialogue Consultants (1992), in a report to the New Zealand Ministry for the Environment, described sustainability as an 'absent referent' – a term of reference seldom defined accurately. It is clear from the burgeoning sustainability literature that there is no single definition of sustainability; indeed different disciplines interpret the concept in fundamentally different ways. A comprehensive review of the sustainable development literature by Pezzoli (1997a, 1997b) arranges these interpretations into eleven categories.[3] Pezzoli's classification has been criticised as prejudiced towards the social sciences and humanities, ignoring significant ecological and scientific literature. The focus of this Chapter is specifically on the economic, ecological, and thermodynamic interpretations of sustainability, i.e. those foundational disciplines of ecological economics.[4]

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[2] The international policy approaches to sustainability emphasise the social, institutional, economic and environmental aspects of sustainability within frameworks that seek to balance or integrate key sustainability factors (Patterson, 2002b). In particular, policy agencies have promoted perspectives that have attempted to integrate the social, economic and environmental dimensions of sustainability.

[3] These categories include policy and planning; social conditions; environmental law; environmental sciences; eco-design and the environment; ecological economics; eco-philosophy; environmental values and ethics; environmental history and geography; utopianism, anarchism and bioregionalism; and political ecology. Pezzey (1992) provides a similar gallery of definitions.

[4] It is beyond the scope of this thesis to review all theoretical interpretations of the sustainability concept. Similarly, coverage of the economic, ecological and thermodynamic interpretations of sustainability is limited to key contributions in these disciplines.

2.1 Economic Interpretations of Sustainability

Early classical interpretations of sustained economic growth were largely pessimistic in their assessment of human ingenuity in overcoming issues of resource scarcity and environmental degradation. For example, Malthus (1864/1798) envisaged an absolute scarcity effect with the finiteness of natural resources constraining growth. World events, such as World Wars I and II, the Great Depression, the rise of Communism, and strong economic growth in Western countries following World War II, saw thinking on issues of resource scarcity wane. Understanding how economic production and consumption patterns might grow, or at least be sustained, to ensure human social welfare intertemporally, has been a primary focus of contemporary economic theorists (Ramsey, 1928; Domar, 1946; Hicks, 1946; Solow, 1956, 1986; Kaldor, 1957; Arrow, 1962; Dixit and Stiglitz, 1977; Hartwick, 1977; Dasgupta and Heal, 1979; Romer, 1986; Lucas, 1988). In this way, economists recognise that two distinct forms of sustainability operate over time, namely sustainable economic growth (increasing per capita production and consumption) and sustainable economic development (non-declining per capita production and consumption). Moreover, economists argue that sustainability requires capital stocks[5] to be increased, or at least maintained, from one generation to the next. A key tenet of the contemporary economic view on sustainability is that growth, as well as maintenance, of capital stocks may be achieved by substitution between the different forms of capital. More contentiously, economists are optimistic that technological change will mitigate any resource scarcity or any degradation in the assimilative capacity of the environment.

2.1.1 Classical Economic Perspectives

The Physiocrats, led by Francois Quesnay, believed agriculture to be the basis for prosperity. They envisaged land as the only true factor of production, generating more wealth than is invested in its tillage by labouring farmers (Pribram, 1983; Spiegel, 1991; Victor, 1991). Quesnay argued that all economic activities of production by humans should be governed by the 'natural order' (Foley, 1973). This implies that all individuals have the right to enjoy the fruits of their own labour, provided that such enjoyment is compatible with the rights of others (Schumpeter, 1954; Screpanti and Zamagni, 1993). Embedded in this thinking are the notions of intra- and intergenerational equity (Neumayer, 2003).

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[5] Herfindahl and Kneese (1974, p.68) define capital as "anything which yields a flow of productive services over time and which is subject to control in production processes". Four forms of capital are typically recognised: (1) manufactured – as created by economic activity, (2) natural – as provided by the environment, (3) human – knowledge and skills, and (4) cultural – social and institutional structures.

In his 1776 work, *The Wealth of Nations*, Adam Smith envisaged arrangements in an economy organised on the basis of competitive markets, through which the selfish behaviour of individuals could serve the collective interest of society (Raphael, 1985; Common, 1988; Kula, 1994). Smith also distinguished between the 'natural price' of a commodity, determined by the amount of embodied labour, and the market price of that good, determined by its market scarcity (Hollander, 1973; Raphael, 1985). While Smith emphasised that agricultural productivity[6] could be increased through capital accumulation, he did not, as Malthus, Ricardo and Mill later did, conceive of diminishing marginal returns[7] from land-based production (Barbier, 1989).

In 1798 Malthus published *An Essay on the Principle of Population*, in which he argued that the human population increases geometrically, whilst land reserves increase only arithmetically (Barnett and Morse, 1963; Tisdell, 1990; Ekins, 2000). Malthus considered population growth unsustainable because it exceeded the carrying capacity of the natural resource base, in contrast to the Physiocrats and Adam Smith, who had emphasised nature's unlimited endowments (Paglin, 1961; Fisher, 1981; Barbier, 1989; Coombs, 1990; Tisdell, 1990). Malthus foresaw an absolute scarcity effect where the finiteness of land or other natural resources would act as a binding constraint on population and economic growth. Only once the entire available stock of the natural resource is utilised, is the Malthusian scarcity effect evident, usually manifesting as rising production costs or market prices. At this point, rising production costs are ineffective in encouraging substitution amongst factors of production. Consequently, economic activity is abruptly halted with no possibility of mitigating the negative effects of diminishing returns on economic output (Barbier, 1989; Pearce and Turner, 1990; Kula, 1994; Ekins, 2000).

David Ricardo's (1973/1817) analysis of the land sustainability problem was more rigorous than that of Malthus. He suggested that land and, by implication, other resources would be subject to diminishing marginal returns because the best land is exploited first. Rather than a catastrophic decline in human population as it overshot its carrying capacity, Ricardo foresaw a slow and gradual reduction in economic returns as the economy reached a stationary state. He concluded it would be necessary to invest greater amounts of capital and labour into progressively less fertile land (Pearce and Turner, 1990; Tisdell, 1990; Kula, 1994; Neumayer, 2003), with food

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[6] Smith argued that the welfare of a nation's people, and the competitiveness of that nation in trade, would be determined by economic growth. According to Smith, the primary factors that promote the growing stock of a nation's wealth are the division of labour and capital accumulation (Hollander, 1973; Oser and Brue, 1988).

[7] The law of diminishing returns suggests that increasing amounts of a variable input, such as labour or capital, combined with a fixed amount of another input, such as land, leads to a decline in the additional amount produced for each successive increment of the variable input (Barbier, 1989; Rees, 1990; Young, 1992).

resources ultimately diminishing over time as the population increased (Schumpeter, 1954; Samuelson and Nordhaus, 1985; Lee, 1989). Thus, Ricardo viewed scarcity as a relative effect. As progressively inferior resources are utilised, the cost of production rises through increasing price movements. The economic system might respond by substituting other factors of production, such as labour or capital, for the depleting natural resource. Without such substitution, increasing resource scarcity might impede economic growth, and the economy may reach an undesirable stationary state (Samuelson and Nordhaus, 1985; Barbier, 1989; Kula, 1994).

In his *Principles of Political Economy* published in 1848, Mill reformulated the Malthusian and Ricardian doctrines of resource scarcity. He particularly emphasised the concept of stationary state[8], the point at which economic progress would cease, which is a key principle in modern sustainability literature. Like Ricardo, Mill accepted the notion that diminishing marginal returns from agriculture would eventually suppress economic development and population growth (Hollander, 1985; Coombs, 1990; Kula, 1994). Nevertheless, Mill supported the idea that the emergence of the stationary state might be alleviated by technological progress (Robinson, 1989; Coombs, 1990; Kula, 1994). He argued that before the arrival of the stationary state, the 'progress of civilisation' would attain a standard of living comfortable for all humankind (Schwartz, 1972).

In 1867, Karl Marx, in his work *Das Kapital*, shared the classical economist's outlook of a dismal future for the labouring classes, and utilised a labour theory of value.[9] Marx made no mention of a constraint on economic production imposed by natural resource scarcity (Barbier, 1989; Lee, 1989; Robinson, 1989; Tisdell, 1990); however, according to his theory, nothing apart from human labour, including natural resources, can have value (Georgescu-Roegen, 1971; Gowdy, 1984; Lee, 1989). Marx asserted that only natural resources in the form of raw materials have value, since only these possess an embodiment of labour. Marx perceived science as humanising nature, turning the inherent value of natural resources, which he considered to be 'gratis'[10], into use value (Georgescu-Roegen, 1971; Gowdy, 1984; Sowell, 1985; Barbier, 1989).

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[8] In his writings concerned with the sustainability of the economic system and human welfare, Herman Daly draws upon Mill's doctrine of the stationary state. However, Daly argues that thermodynamic limits dictate (1) the maximum sustainable rate of resource throughput in the economy; (2) the extent of technological progress, and (3) the extent to which manufactured capital can substitute for natural capital within the production process (Daly, 1973, 1987, 1991a, 1992, 1994).

[9] Smith, Malthus, Ricardo and Mill subscribed to a labour theory of value, i.e. that the price of a commodity was determined by the cost of its production, with the ultimate cost to production being labour (Tisdell, 1990; Spiegel, 1991; Hodgson, 1993; Screpanti and Zamagni, 1993).

[10] In Marxist analysis, the term 'gratis' refers to those objects that are granted or gifted by nature (Georgescu-Roegen, 1971; Barbier, 1989).

2.1.2 Emerging Neo-Classical Economic Perspectives

In 1871, Menger, in *Principles of Economics*, argued the possibility and importance of substitution between factors of production (Christensen, 1989; Screpanti and Zamagni, 1993). In his analysis, Menger assumed that the inputs of land, capital and labour into the production process could be varied, and smoothly substituted for one another (Alter, 1982). Using the example of agriculture, he argued that economic output need not necessarily be constrained by the scarcity of any one productive input, such as capital or labour, since more land or fertiliser could be employed (Christensen, 1989).

In his 1874 work *Elements of Pure Economics*, the French economist Leon Walras conceptualised machinery and land as forms of capital that produce consumer income and flows of producer services (Walras, 1954/1874; Jaffe, 1976; Christensen, 1989). Walras also proposed the concept of general economic equilibrium[11] in which, through a framework consisting of the basic price and output interrelationships for the entire economy, he demonstrated mathematically that all prices and quantities produced would adjust to mutually consistent levels (Schumpeter, 1954; Oser and Brue, 1988; Screpanti and Zamagni, 1993; Ruth, 2002).

In 1890 Marshall published his *Principles of Economics*, in which he agreed with Ricardo's idea that any scarcity of fertile land would lead to increased market prices for agricultural goods (Barbier, 1989; Robinson, 1989). However, Marshall argued that any negative effects resulting from resource scarcity and diminishing returns in land based production would be offset by improvements in the organisation and knowledge of agriculture, as well as technological innovation (Marshall, 1949/1890; Barbier, 1989; Pearce and Turner, 1990; Neumayer, 2003). Marshall, like Mill, acknowledged that nature provides aesthetic services to humans which conform strictly to the Ricardian doctrine of diminishing returns. He argued, however, that the use of non-market environmental services by humans should command a rent because some environmental externalities are not captured by market prices (Marshall, 1949/1890; Barbier, 1989).

[11] Krelle (1984) defines economic equilibrium as a state where the rate of capital accumulation equals the growth rate of labour plus increases in labour productivity.

William Stanley Jevons, an early marginalist[12], was concerned with the issue of natural resource scarcity. In his work *The Coal Question*, Jevons (1909/1865) asserted that the inevitable exhaustion of British coal reserves posed a threat to the nation's sustained economic growth (Barbier, 1989; Nentjes and Wiersema, 1992; Ekins, 2000). Jevons was pessimistic about the coal exhaustibility issue, and was convinced that no other fuel, not even petroleum, could substitute for coal in the future (Common, 1988; Barbier, 1989; Kula, 1994; Neumayer, 2003).

Between 1890 and the early 1970s, neo-classical economics, with its belief in the capacity of the market to ensure the efficient allocation of resources (allocative efficiency), came to dominate Western economic thought (Rima, 1986; Common, 1988; Victor, 1991; Screpanti and Zamagni, 1993). With the exception of Hotelling (1931) and Scott (1955), issues of sustainability were largely overlooked for the best part of the twentieth century. The main world events of this period, such as World Wars I and II, the Great Depression and the rise of Communism, had little to do with the environment or the concept of sustainability. During this period, public policy and government was dominated by social issues such as unemployment and economic reconstruction, resulting in a lapse in any serious academic and theoretical investigation of sustainability issues. During the earlier half of the twentieth century, the macro-economic ideas of John Maynard Keynes strongly influenced government policy, resulting in the adoption of a new form of welfare economics by Western governments. Economic growth became the overriding concern in the 1950s and 1960s, and was viewed by economists as the most important determinant of human welfare (Daly, 1973; Mishan, 1977; Bartelmus, 1994; Reid, 1995).

Over this period, the issue of the ecological sustainability of economic activity was overtaken by a belief that the power of technology, human ingenuity and market mechanisms could overcome any natural resource or environmental constraint. This worldview was typified and supported by the evidence of Barnett and Morse (1963), who tested the implications of natural resource scarcity on extraction costs and market prices. They found that natural resources were steadily reducing in price relative to labour and were in fact becoming less scarce. Barnett and Morse (1963) concluded that the diminishing returns encountered when employing progressively inferior natural resources would be overcome by development or discovery of alternative resources of equal, or even superior, economic quality to those replaced. Studies undertaken by Weinstein and Zeckhauser (1975), Pindyck (1978) and Heal and Barrow (1980) have corroborated these results, while analysts such as Solow (1974), Stiglitz (1974), Kamien

[12] Around 1870, classical economics began to transform into neo-classical economics, a process which involved two theoretical changes: economists abandoned the embodied labour theory of value that had been the mainstay of classical economic analysis, and the predominant method of analysis shifted to marginal analysis.

and Schwartz (1978) and Dasgupta and Stiglitz (1981) have concluded that it may be optimal to deplete an exhaustible resource completely, if future technologies and perfect substitutes exist. However, Chapman and Roberts (1983), Hall *et al.* (1986), Norgaard (1990) and Ekins (2000), note that the Barnett and Morse work assumes technological progress will continue to mitigate any resource scarcities. Although their evidence strongly suggests this is true for the period covered by the study, this does not prove that the trend will continue *ad infinitum.*[13]

2.1.3 Neo-Malthusian View[14] and its Repudiation

Throughout the 1960s and 1970s, the economic growth objective and economists' faith in the capacity of the market to ensure efficient resource allocation, came under attack from non-economists. This scepticism coincided with the emergence of the conservation movement and the realisation of several environmental problems which the market had obviously failed to mitigate (Jacobs, 1991; Ayres, 1993a; Reid, 1995), including soil erosion, deforestation, desertification, the salinisation of land and water, and species extinction. During this period, ecologists actively questioned the compatibility of the economic growth objective with the continued preservation of the environment.[15]

The Limits to Growth study (Meadows *et al.*, 1972), financed by the Club of Rome, utilised a system dynamics model of the world's population and economic system. Reflecting the emerging neo-Malthusian view, the study forecast the eventual collapse of the global economy sometime in the 21st century, resulting from a growing human population and economy outstripping the environmental carrying capacity. Meadows *et al.* (1972) recommended that economic growth be abandoned as a key economic policy in industrialised nations.

The Limits to Growth study received a largely hostile and highly critical reception from mainstream economists who argued that the model failed to account for the capacity of the market to compensate for exhausting resources (Beckerman, 1974; Lecomber, 1975, 1979; Neumayer, 2003). An extensive and passionate literature followed in which the economists dismissed the doomsday arguments of the ecologists and other neo-Malthusians.[16]

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[13] There may, for example, be thermodynamic limitations to technological progress.

[14] Further elaboration on these neo-Malthusian ideas is contained in Section 2.2.1.

[15] Notable publications included *The Silent Spring* (Carson, 1962), *The Economics of the Coming Spaceship Earth* (Boulding, 1966), *Famine* (Paddock and Paddock, 1967), *Population Bomb* (Ehrlich, 1968), *Tragedy of the Commons* (Hardin, 1968), *Small is Beautiful* (Schumacher, 1973), *A Blueprint for Survival* (Goldsmith *et al.*, 1972), *The Closing Circle* (Commoner, 1972), and *The Poverty of Power* (Commoner, 1976).

[16] In a comprehensive critique of the Limits to Growth study, Sussex University's Science Policy Research Unit (Cole *et al.*, 1973) re-ran Meadows' model with different assumptions and produced more positive results. They replaced the key assumption of absolute limits to natural resource availability with

Maddox (1972) refuted the pessimism of the Limits to Growth study in *The Doomsday Syndrome*, claiming that human welfare was improving, and that natural resources were becoming more abundant.[17] He further argued that human ingenuity would solve the problem of energy resource scarcity, and that countries suffering famine would produce food surpluses by the end of the 1970s. Similarly, Simon, in *The Economics of Population Growth* (1977) and *The Ultimate Resource* (1981), argued that population growth was beneficial, as it provided a continual source of human ingenuity with which to overcome problems of resource scarcity.

Goeller and Weinberg (1976) also emphasised human ingenuity and technological progress in their article *The Age of Substitutability*, in which they described how technical change had led to alternatives in mercury-based technologies. Similarly, in his book *In Defence of Economic Growth*, Beckerman (1974) suggested that future technological efficiency would enable society to continue to pursue economic growth. Solow (1974, p.11) emphasised the importance of substitutability, "If it is very easy to substitute other factors for natural resources, then there is in principle no problem. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe". The optimistic view on substitutability is that "reproducible capital is a near perfect substitute for land and other exhaustible resources" (Nordhaus and Tobin, 1972, p.204).[18]

In *The Next 200 Years,* Kahn *et al.* (1976) argued strongly against the neo-Malthusian position. He optimistically maintained that the economy could grow almost indefinitely in the future, unconstrained by natural resource scarcity, leading to an increased standard of living for all. Later, Simon and Kahn (1984) argued that the Earth's endowments of natural resources were more than able to meet the needs of a growing economy and human population.

2.1.4 Contemporary Neo-Classical Economic Perspectives

Neo-classical economists have investigated how economic activities might be sustained using exhaustible and renewable natural resource stocks. This perspective views the environment as a source of resource inputs for economic production. Neo-classical economists have also theorised about the effects of pollution emissions on economic activities, regarding the

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the assumption of exponential increases in available natural resources through discovery, recycling and improved pollution control (Cole *et al*., 1973; Ayres, 1993a).

[17] Hall *et al.* (1986) suggest that resources as a percentage of US GNP have risen from 4 to 8 percent from 1973 to 1985 after remaining constant for the previous 70 years.

[18] Nordhaus later changed his views on substitution, stating that: "There are simply no substitutes for many of today's uses of fossil fuels" (Nordhaus, 1990, p.20).

environment as a sink for economic waste (Dasgupta, 1982; Klaassen and Opschoor, 1991; Jongeneel, 1992). In this perspective, pollution is considered the inevitable result of economic extraction, production and consumption activities (Baumol and Oates, 1979; Krelle, 1984; Klaassen and Opschoor, 1991). The neo-classical economic approach to sustainability represents the mainstream economic approach and is inherently optimistic. According to this approach, economic activities can be sustained indefinitely because of (1) market mechanisms which augment technological progress, and (2) substitution between factors of production (Victor, 1991; Ekins, 2000; Pearce and Barbier, 2000; Booth, 2004).

2.1.4.1 Exhaustible Natural Resources and Sustainability

The Hotelling Rule

The Hotelling rule (after Hotelling, 1931) has provided the basis for much of the contemporary neo-classical literature on resource scarcity (Solow, 1974, 1986; Stiglitz, 1979; Fisher, 1981; Siebert, 1981; Kemp and Long, 1984; Hartwick and Olewiler, 1986). Drawing on the Ricardian doctrine of relative scarcity, Hotelling argued that the market price of an exhaustible natural resource, less its extraction costs, rises over time at a rate of interest commensurate with the increasing relative scarcity of that resource (Hotelling, 1931; Ruth, 1993, 2002; Common, 1995; Ekins, 2000; Neumayer, 2003). The Hotelling rule, as recorded by Common and Perrings (1992), can be written as,

$$\frac{Pi(t_1)}{Pi(t_2)} = r \quad \text{with}\ Pi(t_2) \neq 0, \qquad (2.1)$$

where r is the interest rate or discount rate, and $Pi(t)$ the *in situ* price of the ith resource at time t.

The Hotelling rule suggests that as the relative scarcity of an exhaustible resource increases, its market price will also increase, with a corresponding fall in demand for that resource. According to Hotelling (1931), the optimum rate of depletion[19] occurs when, simultaneously, a resource is exhausted and demand falls to zero, at which time the use of that resource in production ceases (Hotelling, 1931; Barbier, 1989; Ruth, 1993, 2002). Combined with the work of Ramsey (1928), whose approach required a pattern of investment in manufactured capital, the Hotelling rule may be used to sustain social welfare intertemporally[20] (Solow, 1974, 1986;

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[19] Known as the 'rate of efficient intertemporal allocation'.

[20] For a mathematical description of the Hotelling rule operating with the Ramsey rule, refer to Neumayer (2003, pp.201-208).

Dasgupta and Heal, 1979; Hartwick and Olewiler, 1986). Furthermore, the Hotelling rule has been used by neo-classical economists in the search for empirical evidence of the market's ability to mitigate natural resource scarcity in the long term, and to find substitutes for exhaustible resources in the production process (Goeller and Weinberg, 1976; Frank and Babunovic, 1984).

Authors like Smith (1981), Bretschger (1999), Ekins (2000) and Neumayer (2003) have questioned the validity of the Hotelling rule. For example, Smith (1981) examined the price movements of twelve non-renewable resources (four fossil fuels and eight metals) and found that only two of the twelve supported the rule. He concluded that extraction costs, new discoveries, changes in market structure and institutional effects also play an important role in explaining price change. Bretschger (1999) added lack of long-term ownership (shortening the time horizon for optimal use of the resource) and the existence of backstop technologies (which may substitute for the resource) as further reasons for price variation. Neumayer (2003) argued that the difficulty in measuring resource rent over time has been a major obstacle in empirical attempts to validate the Hotelling rule.

The Hartwick Rule

Hartwick's rule (after Hartwick, 1977, 1978) states that the welfare of future generations may be satisfied by investing rents derived over time from the use of exhaustible natural resources into the acquisition of manufactured capital, ensuring the total capital stock remains unchanged. Dasgupta and Heal (1979) model the Hartwick rule by employing the Cobb-Douglas production function[21]:

$$Y = f(K,R) = K^{a1}R^{a2} \text{ with } a1, a2 > 0 \text{ and } a1 + a2 < 1, \qquad (2.2)$$

where Y, K and R respectively represent an output of manufactured capital, an input of manufactured capital, and an input of an exhaustible natural resource. The f is used to denote a production function, and a the elasticities of substitution between inputs. This production function has two noteworthy properties. First, an input of natural resources is held to be essential for production, i.e. without such an input no output could be produced. Second, there are perfect substitution possibilities between all inputs into the production process, i.e. the elasticities of substitution, $a1$ and $a2$, always sum to greater than zero.

[21] A production function states the functional relationships between inputs and outputs in the production process (Blaug, 1985; Baumol *et al.*, 1991).

It is the second property of the production function that is most contentious. Dasgupta and Heal (1979, p.200) debate the possibilities of such substitution, stating that the "crucial question is whether or not $a1>a2$ ... since these two parameters represent the elasticities of substitution with respect to manufactured capital and the exhaustible resource". If $a1>a2$ then, despite any increasing scarcity of the natural resource R, manufactured capital can be considered sufficiently important in production to allow the possibility that the output level Y could be maintained permanently. However, if $a2>a1$, i.e. the exhaustible resource is essential to production, output must eventually fall to zero. Dasgupta and Heal (1979) argue optimistically that, given the technological progress of the last 300 years, they would expect that $a1>a2$, possibly even four times greater.[22]

The Hartwick rule and the neo-classical position on economic sustainability rest upon two contestable assumptions: first, to enable the production process to be sustained, manufactured capital can substitute for natural resources as a production input, and second, ongoing technological progress will at least keep pace with the depletion of exhaustible natural resources (Victor, 1991; Munasinghe and McNeely, 1995; Reid, 1995; Neumayer, 2003). In the words of Dasgupta and Heal (1979, p.205), "even in the absence of technological progress, exhaustible resources do not pose a fundamental problem" if reproducible capital is sufficiently substitutable for natural resources. They further conclude that technological progress improves possibilities for sustainable increases in output.

2.1.4.2 Renewable Natural Resources and Sustainability

Early studies on optimal rates of renewable resource harvesting focused on forestry and fishery depletion (refer to Gordon, 1954; Scott, 1955; Faustmann, 1968). These, and many later studies, looked at additional factors not normally considered in determining optimal rates of exhaustible resource depletion, such as natural (biological) growth rates, reproduction and mortality.

Maximum Sustainable Yield

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[22] Victor (1991) has argued that the elasticities of output formation might be used as indicators of sustainability since, according to neo-classical economists, it is these parameters that will alleviate, through substitution effects, any future resource scarcities or environmental degradation. Using mathematical models, he demonstrates several critical problems with elasticities of output as possible indicators. For example, he argues that assumptions of perfect markets are unrealistic. If markets are perfect, and natural resources are being allocated efficiently over time, i.e. without policy intervention, then sustainability indicators are unnecessary. However, markets are generally acknowledged as imperfect; this results in policy intervention and sustainability indicators are essential. Nevertheless, sustainability indicators based on economic valuation cannot be implemented as ultimately they must rest on the assumption of perfect markets – a prerequisite position that has already been shown to be wrong.

In neo-classical economic analysis concerned with sustainability, a natural resource regeneration function is used to relate the growth rate of a renewable resource to the size of the resource stock. Klaassen and Opschoor (1991) state that this regeneration function typically takes the form,

$$S = \frac{dR}{dt} = aR\left(1 - \frac{R}{C}\right) \text{ with } C \neq 0\,, \qquad (2.3)$$

where S denotes the increase in the stock of the renewable resource over time, a the coefficient of natural growth rate, R the resource stock, and C the environmental carrying capacity. Assuming that the renewable resource is essential for production and that human population growth is zero, neo-classical economists conclude there is a maximum level of resource harvest that can be sustained indefinitely, termed the Maximum Sustainable Yield (MSY)[23] (Clark, 1976; Baumol and Oates, 1979; Conrad and Clark, 1987; Daly, 1994; Costanza and Patten, 1995). MSY depends on the growth rate, a, and the size, R, of the resource stock (Clark *et al.*, 1985; Conrad and Clark, 1987). If MSY exceeds present levels of harvest, then the resource stock will grow to an optimal point where the regeneration rate is equal to the rate of harvest (Turner, 1988). If economic extraction exceeds MSY, then resource saving technical change or substitution of manufactured capital for the resource, would allow production and consumption to be sustained and resource scarcity to be mitigated, even if the resource was completely depleted (Herfindahl and Kneese, 1974; Baumol and Oates, 1979; Dasgupta and Heal, 1979; Kemp and Long, 1984).

Sustainable Economic Welfare

Siebert (1981, 1995)[24] uses the following welfare function to model sustainable economic development with renewable natural resources:

$$W = U(Ct, R)e^{-rt}dt\,, \qquad (2.4)$$

[23] MSY is an ecological term that represents the theoretical point at which the size of a population is such as to produce a maximum rate of increase.

[24] Siebert (1981, 1995) was amongst the first to formalise this model of sustainable economic development – recent developments in the field are discussed by Pezzey (1997). Other authors have developed similar indices. Daly and Cobb (1989), for example, based on the work of Nordhaus and Tobin (1972), advocate the use of an Index of Sustainable Economic Welfare (ISEW). The ISEW has subsequently been reformulated as the Genuine Progress Indicator (GPI) by including additional costs and benefits.

where W represents economic welfare, U utility, C consumption, R a renewable resource stock and rt a social discount rate. In Siebert's model resource regeneration, R', is a function of the natural growth rate less total extraction, Xt (the sum of extraction, X, and consumption, C), while net capital accumulation, K', is a function of production less consumption, $K'=f(K, X)-C$. Using these functions, Siebert (1981) investigates the potential for sustainable economic growth given the possible use of the renewable resource as (1) a consumer good and (2) a factor of production. He concludes that, in the absence of technical progress or human population growth, the rate of use of a renewable resource as a consumer good is optimal when the rate of resource regeneration equals the rate of social discount, $R'=rt$. If the social discount rate[25] exceeds the maximum rate of regeneration, $rt>R'$, the renewable resource will become depleted, resulting in a decline in consumption over time. If the discount rate is less than the rate of resource regeneration, $rt<R'$, then consumption can be sustained, but only if present generations consume less than future generations (Siebert, 1981).

According to Siebert (1981), if the renewable resource is a factor of production, then in order to achieve optimal economic welfare, capital accumulation and resource harvest should be controlled in such a manner that the contribution of the resource to production equals both the social discount rate and regeneration rate of that resource. A sustainable pattern for optimal renewable resource allocation over time requires that any marginal increase in production using the resource must equal the marginal sacrifices imposed upon future generations (the socially acceptable opportunity cost), plus the rate of resource saving or resource substituting technical progress (Siebert, 1981).

2.1.4.3 Pollution and Sustainability

Siebert (1987) models economic development with pollution emissions as:

$$W = U(C,P)e^{-rt}dt\,, \qquad (2.5)$$

where W is economic welfare, U the utility stream, C total consumption, P the stock of pollutants, and rt the social discount rate. In Siebert's function, pollution, P', is a result of production, $f(K,P)$, which in turn is a function of capital, K, and also the stock of pollutants, P,

[25] Consumer welfare utility and producer profit must be maximised not only in the current period, but also over time. Economic agents are seen to express a social discount rate that allows for the intertemporal distribution of the consequences (forgone utility or profit) resulting from their consumption and production activities. Typically, the social discount rate is levied so that present utility/profit is preferred over future utility/profit (Randall, 1987; Ruth, 1993).

since pollution is taken to have a negative impact on production activities.[26] Pollutants are either degraded naturally, aP, or are abated by environmental protection capital, bKe. Thus, $P' = f(K,P) - bKe - aP$. Productive output can be either consumed, C, reinvested in pollution control equipment, Ie, or reinvested in the production of further capital to permit capital accumulation, $K' = f(K,P) - C - Ie$.

According to Siebert (1987), if pollution affects only the direct utility value of a resource, and no pollution abatement capital is employed, then sustainable economic development would require pollution emissions to equal the capacity of the environment to assimilate waste. The possibility of sustainable economic development will be determined by the size of current stocks of production capital and pollutants, while a growth in these stocks (or in society's consumption) up to an optimum level will depend on the waste assimilative capacity of the environment. Beyond that point, society's preferences for consumption and environmental quality would determine the possibility of sustainable economic development (Siebert, 1987).

Should pollution emissions impair the regeneration rate of a renewable resource that serves as a production input, the possibility of sustained economic development might be further jeopardised. Siebert (1982) models sustainable economic welfare (W) with renewable resources and pollution as follows:

$$W = U(X)e^{-rt}dt, \qquad (2.6)$$

where U represents the utility stream, X extraction, and rt the social discount rate. In this function, welfare, W, is dependent upon the volume of resource extracted for use in direct consumption or in production processes. The regeneration of a resource, R', is equal to the growth rate of that resource multiplied by the size of the resource stock, less total extraction, Xt, and the self-cleansing capacity of the environment, aP. Thus, $R' = G(R) - X - aP$. Pollution accumulation, P', results from resource extraction, X, less the self-cleansing capacity of the environment, aP, or $P' = X - aP$.

According to Siebert (1982), sustainable economic development is possible where the social discount rate equals the regeneration rate of the resource. A minimum level of extraction, determined by the size of the human population and desired levels of consumption per capita, is

[26] In neo-classical economics, pollution is seen to have two effects on economic activity: (1) a direct negative impact on production processes, e.g. degraded air or water quality, and (2) an impact on the reproductivity of a renewable natural resource that serves as a factor of production, e.g. pollution may impair the growth rate of a fisheries stock.

assumed to be necessary to provide for economic development. Even if pollution stocks are low, if this minimum level of extraction exceeds the regeneration rate of the resource, then the resource stock will be driven to zero, and production and consumption at those levels may not be sustainable. Of course, the negative effects of resource depletion on productive output may be offset by technical progress. Sustainable economic development might be possible, subject to the effects of pollution emissions on the regeneration of the resource, if the discount rate or rate of extraction is below the point of MSY.

2.1.4.4 Weak and Strong Sustainability

Several interpretations of sustainability based on capital theory have been developed. According to these interpretations, a necessary condition for sustainability is that total capital (natural, manufactured, human, social) must at least be maintained from generation to generation (Pearce and Barbier, 2000; Neumayer, 2003). Pearce and Barbier (2000) argue that economists are generally split into two camps over the role played by natural capital in achieving sustainability with the pivotal difference being whether or not natural capital has a "unique or essential role in sustaining human welfare" (Pearce and Barbier, 2000, p.23). These contrasting viewpoints are typically known as weak and strong sustainability (Ekins, 2000).[27]

Weak Sustainability

The weak sustainability interpretation asserts that the economy is considered sustainable as long as total capital is maintained from generation to generation (Solow, 1986, Hartwick, 1978; Neumayer, 2003; Booth, 2004). This is an optimistic perspective which envisages technology and innovation overcoming resource scarcity and environmental problems. The assumption that this may be achieved through market forces, by providing incentives for innovation, typifies the perspective of writers like Kahn (1979), Simon (1981), and, in the New Zealand context, political activists like McShane (1998). The weak sustainability interpretation further assumes that manufactured capital is a true substitute for natural capital (Neumayer, 2003; Booth, 2004).

Pearce and Atkinson (1993) present a weak sustainability indicator.[28] Assuming the neo-classical possibility of complete substitutability between manufactured capital and natural

[27] The weak sustainability paradigm is often referred to as 'Solow' (after Solow, 1974, 1986) or 'Solow-Hartwick' sustainability (Common and Perrings, 1992; Neumayer, 2003).
[28] Hamilton (1994) introduces a similar indicator referred to as 'Genuine Savings'. Neumayer (2003, p.128) considers Hamilton's indicator the "theoretically correct measure of weak sustainability". Genuine savings (GS) considers all utility-relevant stocks of capital, including natural, human and social, to be derived from traditional net savings. Neumayer (2003) demonstrates mathematically that an

capital, as well as ongoing technological progress, Pearce and Atkinson (1993) formulate a simple savings rule to rate the sustainability of a nation's economy at a given time:

$$Z > 0 \text{ if } \frac{S}{Y} > \left(\frac{D_M}{Y} + \frac{D_N}{Y} \right) \text{ with } Y \neq 0, \tag{2.7}$$

where Z is the sustainability index for a nation, S the savings or the accumulation of capital, D_M the value of depreciation on manufactured capital, D_N the value of depreciation on natural capital, and Y income. Utilising the above savings rule, Pearce and Atkinson (1993) formulate a weak sustainability indicator for a nation's economy as:

$$Z = \frac{S}{Y} - \frac{D_M}{Y} - \frac{D_N}{Y} \text{ with } Y \neq 0. \tag{2.8}$$

Using the same notation as Equation 2.7, Z produces a measure for deviation from marginal sustainability for a nation. The larger any negative value of Z, the greater the effort required to return the economy to a sustainable path relative to national income (Pearce and Atkinson, 1993).

Strong Sustainability

Pearce and Turner (1990) of the London Environmental Economics Centre (LEEC) present a strong sustainability interpretation, arguing that a prerequisite for achieving sustainable economic development is the maintenance of a constant natural capital stock.[29] They challenge the weak sustainability argument, presenting five reasons why the substitution of manufactured capital for natural capital within production processes is often impossible: (1) manufactured capital is not independent of natural capital because the latter is often needed to create the former; (2) natural capital fulfils other economic functions including basic life support, and is multifunctional to an extent not shared by manufactured capital; (3) natural capital cushions the economy against environmental shocks; (4) natural capital stock should be maintained over time to ensure intergenerational equity; and (5) conservation of the natural capital stock recognises

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economy can only be weakly sustainable if GS<0. Other weak sustainability indicators include the Index of Sustainable Economic Welfare (ISEW) and the Genuine Progress Indicator (GPI).

[29] In this way, strong sustainability can be seen as an application of the 'precautionary principle' (after O'Riordan, 1993) or the 'safe minimum standards' concept (after Ciriacy-Wantrup, 1952). The precautionary principle encompasses two core elements: (1) preventive measures should be taken before definite scientific proof of environmental risk, and (2) while current practice endorses economic activity over environmental protection, the new default position should favour environmental preservation (Ekins, 2000; Neumayer, 2003).

the rights of other species to co-exist with humans. Victor (1991) has also challenged the idea of unlimited elasticity of substitution, proving mathematically that the creation of manufactured capital is constrained by the extent to which it requires inputs of natural capital.

Pearce and Turner (1990) also challenge the technological progress assumption that supports the neo-classical economic approach to sustainability. Like Krutilla (1967), they argue that the type of technological progress envisaged by the neo-classical economists does not necessarily imply less pollution or increased resource saving. Technological progress often tends to augment capital stock and increase economic output, rather than enhance the supply or efficient use of natural resources.

The LEEC theorists distinguish between the neo-classical definition of capital and the notion of 'critical natural capital' (Ekins, 2000, 2003; Neumayer, 2003), recognising that various environmental assets and functions are non-substitutable. They suggest that society should be "circumspect about giving up natural capital" given the uncertainty and irreversibility associated with the impacts of economic activities on the environment (Pearce and Turner, 1990, p.51). Their response is to introduce constraints on both the potential waste assimilative capacity of the environment and the minimum size and quality of natural capital stocks deemed necessary for sustained economic development (Barbier and Markandya, 1989; Pearce *et al.*, 1990; Turner *et al.*, 1994). The LEEC theorists present four possible interpretations for a constant stock of natural capital: (1) the physical quantity of natural resource stocks should remain constant[30]; (2) the total value of the natural resource stocks should remain constant in real terms; (3) the unit value measured in prices of the natural resource services should remain constant in real terms; or (4) the value of the resource product price and quantity used from the natural resource stock should remain constant in real terms.[31]

Hueting *et al.* (1992) provide a strong sustainability indicator for a non-renewable resource. Their approach is to determine the maximum sustainable rate of depletion in a period, using improvements in use-efficiency, recycling or the development of substitutes. In mathematical terms this may be modelled as,

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[30] Pearce and Turner (1990) note the difficulty in commensurating different physical quantities of natural capital stock expressed in different physical units. For example, it is impossible to add together a stock of timber expressed in tonnes and a stock of natural gas measured in joules (Pearce and Turner, 1990; Victor, 1991).

[31] The second, third and fourth interpretations of a constant stock of natural capital offered by Pearce and Turner (1990) all utilise market prices as a source of value. A market-based theory of value has problems – for example, environmental resources such as air and water do not have direct market values, and shadow prices have to be estimated for these resources.

$$d(t) \leq r(t) \times s(t)\,, \tag{2.9}$$

where $d(t)$ is the depletion rate of the resource, $r(t)$ the rate of use-efficiency improvements, and $s(t)$ the stock of the resource.[32] Alternatively, sustainable use of a non-renewable resource may be derived using a minimum life expectancy, $L_{\min}$,

$$d(t) \leq s(t) / L_{\min}\,, \tag{2.10}$$

where $d(t)$ is the depletion rate and $s(t)$ the stock of a resource.

Neumayer (2003) critiques and reviews several possible strong sustainability indicators including Ecological Footprints (after Wackernagel and Rees, 1996), Materials Flow Analysis (after Ayres and Kneese, 1969), and Sustainable National Income (after Hueting, 1980). Ecological Footprints are discussed in greater detail in Chapter 8, while Materials Flow Analysis is covered comprehensively in Chapters 4 and 6. Refer to McDonald (1997) for an in-depth discussion of Sustainable National Income.

Both the weak and strong sustainability indicators require measurement of capital stock, a long recognised area of difficulty in economic theory (Blaug, 1974). Accordingly, some economists prefer to measure flows of goods and services rather than stocks. Although flow indicators such as GDP or an adjusted green GDP are much easier to apply, such measurements tell us nothing about the transfer of wealth between generations.

2.2 Ecological Interpretations of Sustainability

2.2.1 Sustainability of the Biosphere

The works of Kenneth Boulding (1966) and Garret Hardin (1968) have been particularly influential in establishing a foundation for contemporary ecological sustainability theory. Boulding's (1966) *The Economics of the Coming Spaceship Earth* uses a spaceship metaphor to analyse the predicament of humans on a finite planet. Boulding's metaphor stresses the Earth's smallness, overpopulation, and limited resources; most importantly, it emphasises that the Earth is a closed system dependent on material recycling and the linear flow of energy (Booth, 2004). Boulding asserted that matter, energy and information were the fundamental factors of

[32] Ekins (2000) has modified Hueting *et al.*'s (1992) equation to incoporate the sustainable use of environmental functions.

production rather than labour, capital and land. Hardin's (1968) *Tragedy of the Commons* draws an analogy between farmers' overgrazing of the pastoral commons, and the tendency of nations to pollute the global commons in pursuit of economic growth. Hardin comments on the divergence between individual and collective interests in resource use, noting the tendency of individuals to use natural resources opportunistically, to the detriment of the collective interests of others. He also notes the importance of human activity not exceeding the biophysical carrying capacity of the environment – a central tenet of the ecological interpretation of sustainability. Hardin (1968), like Boulding (1966), was pessimistic about technical solutions to sustainability problems, instead emphasising the need to seek social solutions.

The Limits to Growth study (Meadows *et al.*, 1972) provided the ultimate expression of the emerging neo-Malthusian viewpoint of the environmental movement, concluding, "if the present growth trends in world population, industrialisation, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years" (Meadows *et al.*, 1972, p.29). The study's computer simulation analysis demonstrated various scenarios in which the world's population catastrophically overshot its carrying capacity. This work inspired a flurry of publications which debated its central message – the implausibility of infinite growth within the Earth's finite biosphere. For example, Herman Daly's (1977, p.17) *Steady-State Economics* argued for a steady state economy whereby "a constant stock of people and artefacts [is] maintained ... by low rates of maintenance 'throughput' of energy and mass". Georgescu-Roegen's (1971) *Entropy and Economic Progress* also noted that human activity is critically limited by biophysical constraints, but refuted any equilibrium (steady state) ideas, claiming that in an entropic world predicated on the Second Law of Thermodynamics such a state would be physically impossible.

In the early 1970s, ecologists began to apply ecological principles in analysing sustainability. E.P. Odum (1971), Dasmen (1972), Ehrlich *et al.* (1973), and Watt (1973) typified much of the early ecological sustainability theory. Watt (1973), for example, established principles of environmental science based on the fundamental variables of matter, energy, space, time and diversity. Other principles useful in defining the concept of sustainability from an ecological perspective that emerged from this literature include: maintaining human populations within the carrying capacity of the biophysical environment, protecting the biosphere from the risk of sudden collapse or substantial decline, and keeping intact the biosphere's self-organising and species-supporting capacity.

2.2.2 Sustainability of Ecosystems, Communities and Populations

Ecologists are concerned with various levels of organisation: population, community, ecosystem and biosphere. The previous Section focused on the ecological interpretations of sustainability at the biosphere or global level, while this Section focuses on the population, community and ecosystem.

2.2.2.1 Equilibrium Ecology

A fundamental process in ecology is ecological succession – the progressive development of a community of animals, plants and micro-organisms from an embryonic to a mature climax state.[33] A climax community is argued to be relatively stable, diverse (in terms of spatial and species heterogeneity), energetically efficient (energy inputs are required only for maintenance, not growth), complex in terms of niche specialisation and life cycle roles of species, highly developed in feedback control, and characterised by low entropy and high levels of information. The steady state or equilibrium point is where the whole ecosystem is in balance with its abiotic environment and, without exogenous perturbation, its structure and function would persist indefinitely (E.P. Odum, 1983; Ricklefs, 1990; Kay, 1991; Ruth, 1993). The vegetative cover of a particular locality will inexorably move to this equilibrium point after some perturbation or catastrophic event; for example, a forest fire invokes the following successional sequence: bare ground to mosses, lichen, and grasses, to shrubs, to woody hardwoods (e.g. manuka), bird-dispersed trees (e.g. podocarps) and gravity dispersed trees (e.g. beeches). The developing equilibrium between the biological community and its physical environment is dynamic, not static, accounting for the constant adjustments the community makes in response to environmental fluctuations.

Essentially an equilibrium paradigm of ecology has developed, where ecosystems are maintained in a state of balance through the mechanism of homeostasis.[34] Feedback mechanisms ensure that if the ecosystem is perturbed, for example, by a fire or flood, it is returned to its original state through a self-correcting feedback mechanism. The idea of

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[33] The concept of ecological succession can be traced back to the work of Frederic Clements (1916). Odum (1971b) defines the process of ecological succession as (1) an orderly, directional and therefore predictable process of community development that involves changes in species structure and community processes with time; (2) an outcome of the modification of the physical environment by the biological communities, even though the physical environment determines the pattern and rate of change and any development limits; and (3) culminating in a stabilised ecosystem in which maximum biomass and symbiotic function between organisms are maintained at per unit available energy flow. Accordingly, the strategy of succession achieves maximum protection from any perturbations.

[34] According to Miller (1995), the mechanism of homeostasis ensures that the internal state of a system is maintained despite fluctuations in external conditions.

equilibrium in ecology dominated the discipline's thinking on sustainability until the late 1980's (DeAngelis and Waterhouse, 1987). The central tenet of this view of ecosystems is that more diverse ecosystems are more stable and, by definition, sustainable. Under the equilibrium paradigm of ecology, ecological sustainability is defined as a state in which the ecological system has reached its climax stage (Patterson, 2002b). Moreover, the ability to plan rationally for ecological sustainability is relatively simple as the successional pathway is predictable and its climax is known and desirable. Much of the traditional resource management literature (e.g. Burton and Kates, 1965) is predicated on this paradigm.

2.2.2.2 Non-Equilibrium Ecology

The equilibrium paradigm of ecology was extensively challenged in the so-called 'stability-diversity' controversy in the early 1970s. May (1972, p.414), in a watershed paper on the topic, mathematically demonstrated that "too rich a food web connectance, or too large an average interaction strength ... leads to instability ... The larger the number of species, the more pronounced the effect". Empirical support for May's findings was provided by Zaret (1982). Thus, May's (1972) findings overturned a central tenet of the equilibrium paradigm – that diverse communities are necessarily stable. Moreover, May (1974) drew the attention of ecologists to another sobering fact. Because the simplest of non-linear equations could produce chaotic, and therefore intrinsically unpredictable, behaviour, the hope of deriving simple laws for (ecological) systems in which non-linearity is the norm is illusory (Judson, 1994). Kay and Schneider's (1994) thermodynamic analysis of ecosystem behaviour essentially supports May's (1972, 1974) analysis by arguing that, contrary to the assumption of succession theory, there is no single optimum or homeostatic state.

DeAngelis and Waterhouse (1987) provide an excellent synopsis of the non-equilibrium paradigm. Endorsing the work of Wiens (1984), they pictured communities as existing in a spectrum with no single equilibrium point. Figure 2.1 provides a convenient summary of their position – if a ball located at point A may experiences a small perturbation (force) such that it will return to the valley floor after a few oscillations, but a larger perturbation might force it out of the valley to another location which may or may not be at equilibrium.

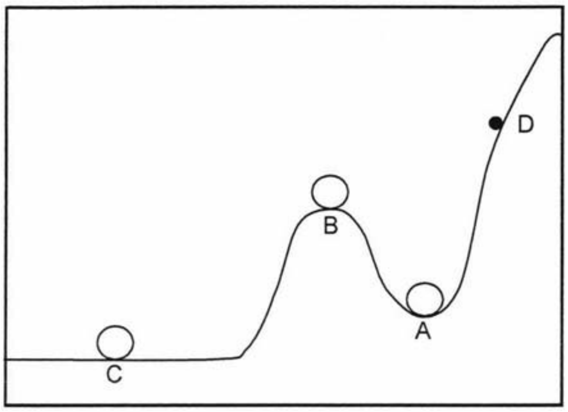

Figure 2.1 **Non-Equilibrium and Equilibrium Points in Ecosystem Dynamics.** Types of equilibrium points: A – stable equilibrium, B – unstable equilibrium, C – neutrally stable equilibrium, and D – not at equilibrium. Adapted from DeAngelis and Waterhouse (1987).

Some ecosystems may have multiple stability states, and such systems may switch to a new steady state when environmental perturbation forces them beyond a certain threshold level.[35] The emergence of new steady state systems may be undesirable for humans, because those states may not sustain current human needs (Holling, 1986, 1995). Uncertainty is also associated with the form any new global steady state ecosystems and the transitional threshold levels of environmental perturbation to the systems (Holling, 1986, 1995; Jansson and Jansson, 1994).

The interpretation of the ecological sustainability concept under the non-equilibrium paradigm becomes more problematic as there is no steady state. At best an ecosystem may persist over time by maintaining itself within lower and upper biophysical limits represented by floors and ceilings (Patterson, 2002b). Under this persistence model, a decline in species numbers and ecosystem functions is permissible as long as the system itself persists. This ecological reality may be unsatisfactory for those approaching ecological sustainability from a perspective which presumes the existence of a balance of nature (Patterson, 2002b)

[35] There is evidence that human activity has already pushed some indigenous ecosystems beyond such threshold levels, leading to those systems finding a new steady state. Overgrazing of the African savannah, for example, has turned grasslands to desert (Holling, 1986, 1995).

2.2.3 Key Ideas in Ecological Sustainability

2.2.3.1 Biological Diversity

The conservation of biodiversity is often seen as a key condition for the maintenance of natural capital[36] and environmental life-support systems[37] – both of which are essential for sustainability (Pearce and Turner, 1990; Westman, 1990; Perrings, 1991, 1994; Ehrlich and Ehrlich, 1992; Karr, 1992; Noss, 1992; Walker, 1992; Pearce and Barbier, 2000). The term biodiversity is often not clearly defined, but is usually used in the literature to refer to the diversity of species within an ecosystem (Wilson, 1988). Diversity may exist at many different temporal and spatial scales – all of which are relevant to the concept of sustainability (Jansson and Jansson, 1994; Pearce and Barbier, 2000).

Functional diversity, for example, describes the activities that different species within an ecosystem perform (O'Neill *et al.*, 1986). A functionally diverse ecosystem typically has many different species performing similar life-support functions i.e. photosynthesis, nitrogen fixation and organic decomposition (Wilson, 1988). Functionally diverse ecosystems are therefore ecologically sustainable, since even if some species are lost with change, the continuance of the key life-supporting functions within the ecosystem is ensured by the presence of the remaining species (Jansson and Jansson, 1994).

Spatial diversity is of crucial importance to the structure and function of an ecosystem. Jansson and Jansson (1994) cite the spatial diversity of oceanic ecosystems as exemplified by the vertical distribution of production and respiration processes with a gradual extinction of sunlight with depth. Temporal diversity may also exist. Flows of energy and matter across an ecosystem's boundary are not necessarily steady, but may occur in pulses. Many species adapt to variations in matter and energy flow though mechanisms such as hibernation; human economic systems, however, attempt to smooth out the natural fluctuations of ecosystems to secure a steady delivery of ecological goods and services (E.P. Odum, 1971; Jansson and Jansson, 1994). The gap between natural environment production, and required human output, is often bridged through the unsustainable use of fossil fuels, fertilisers and technology. A more ecologically sustainable economy would therefore adapt to the temporal diversity in ecosystem output.

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[36] Diversity of species, for example, provides opportunities for the emergence of new species. This serves humans indirectly by supporting other species which may in turn prove to be valuable to humans (Norton, 1986).

[37] Even if some species are lost with change, for example, the continuance of key life-supporting functions may be ensured by those species that remain (Norton, 1986).

2.2.3.2 Ecosystem Stability and Resilience

Since the work of MacArthur (1955), theoretical ecologists have mostly concerned themselves with how diversity leads to stability. Stability is the propensity of an ecosystem to rapidly attain an equilibrium condition in terms of species composition, following perturbation of steady state or stable oscillation. In stable environmental habitats, such as oceans, coral reefs and tropical forests, greater species diversity typically prevails – such ecosystems are however particularly susceptible to change (Holling, 1995). Conversely, in environments susceptible to regular stochastic change, the number of species typically remains low e.g. temperate forest systems (Ruth, 1993). E.P. Odum (1983) argues that this is often a result of species expending more energy in order to survive, leaving less excess energy available for species diversification.[38]

Resilience is the tendency of a system to retain its organisational structure, function and patterns of behaviour, but not necessarily its species composition, following disturbance (Pearce and Barbier, 2000).[39] This is in contrast to stability which is viewed as a narrower term, referring solely to the stability of species composition within populations or communities in the face of disturbance. Ecological resilience, as defined by Holling (1973, 1986, 1995), may be used to define ecological sustainability. Holling's resilience concept can be considered a compromise between equilibrium and non-equilibrium ecology, emphasising the boundary of the stability domain, events far from equilibrium, high variability, and adaptation to change (Holling, 1986; Barbier, 1989). Holling (1973) considers there to be four phases that describe the dynamics of ecosystem development in terms of his 'Figure 8' diagram (Figure 2.2) – an early exploitation phase dominated by opportunistic pioneer species, a conservative climax stage where the ecosystem consolidates and is relatively stable, a release phase where ecosystem structure breaks down due to some external perturbation e.g. pest outbreak, fire, flood or drought, and a reorganisation stage where an ecosystem may return to the same equilibrium point or be jolted to another. Accordingly, an ecosystem may have the ability to absorb change, but such change is to be expected and an ideal steady state end-point is not assumed to exist. Odum (1996) has described a similar picture of ecosystem dynamics, which in this energy flow nomenclature is termed a 'pulsing paradigm'.

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[38] Boltzmann (1905/1974, cited in Odum, 1994, p.6) also recognised this tendency, saying the "struggle for existence is a struggle for free energy available for work". Lotka (1922) similarly suggested that systems prevail that develop designs that maximise the flow of useful energy. Odum (1994) has termed this the 'maximum power' principle.

[39] Common and Perrings (1992) and Levin *et al.* (1998) argue that the resilience concept is not only applicable to ecological systems, but also to ecological economic systems.

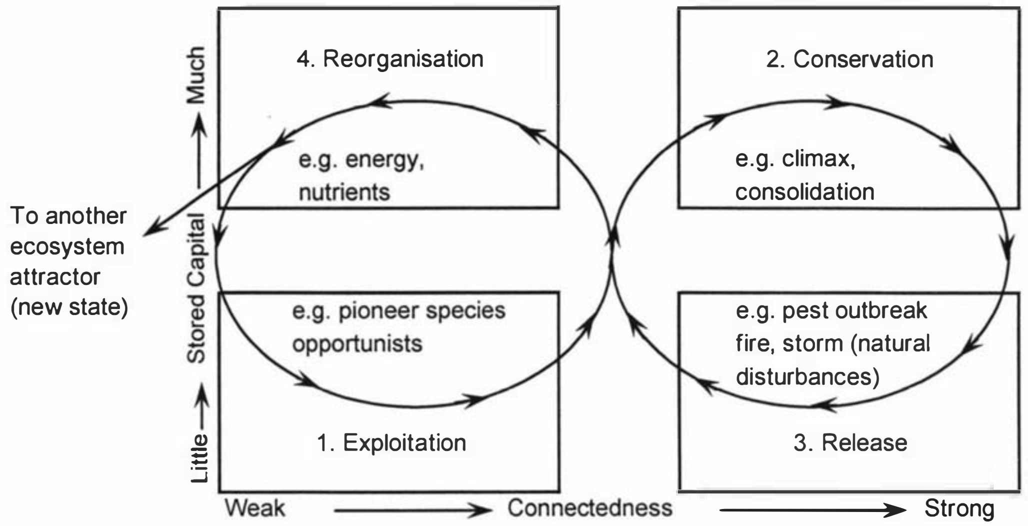

Figure 2.2 **Holling's Four Phase Model of Ecosystem Change and Resilience.** Adapted from Lister (1998) and Pearce and Barbier (2000).

2.2.3.3 Carrying Capacity

Ehrlich (1994) argues that the concept of carrying capacity[40], keeping the scale of human activities within the supportable bounds of the environment, is important in determining the sustainability of such activities. Daily and Ehrlich (1992) note, however, that defining carrying capacity for human populations is problematic. Carrying capacity is a function of both available resource base, and species characteristics (Roughgarden, 1979; Daily and Ehrlich, 1992; Ruth, 1993; Allaby, 1994). Humans, more so than any other species, are able to modify their immediate resource base by trading resources such that a given population may exceed its carrying capacity (Pearce and Barbier, 2000). Furthermore, humans are capable of changing their consumption patterns. These traits introduce significant uncertainty into calculating human carrying capacity (Ehrlich *et al.*, 1977; Holdren *et al.*, 1993; Ehrlich, 1994).

Daily and Ehrlich (1992) and Holdren *et al.* (1993) distinguish between two forms of human carrying capacity, biophysical carrying capacity and social carrying capacity. Biophysical carrying capacity represents the maximum number of people that can be supported by an ecosystem at a given level of human technology. Social carrying capacity is the same as biophysical carrying capacity except that the population must exist within a given system of social organisation with known patterns of consumption and trade. Underpinning such systems of social organisation are knowledge and technologies which may alter carrying capacity (Daily and Ehrlich, 1992; Holdren *et al.*, 1993; Ehrlich, 1994). According to Ehrlich and Ehrlich (1990) and Ehrlich (1994), the world's population has already exceeded the Earth's social

[40] Roughgarden (1979, p.34) defines carrying capacity as the "maximum population size of a given species that an area can support without reducing its ability to support the same species in the future".

carrying capacity[41], and the physical scale of the world economy is too large for the capacity of the life support systems to maintain it over the long run.

Holdren and Ehrlich (1974) and Ehrlich and Ehrlich (1981) have argued that the most crucial role of the environment for humans, is its capacity to absorb economic abuse and continue to deliver environmental life support services. Ehrlich (1994) asserts that the magnitude of peoples' impact on that capacity, denoted *I*, can be determined by the following equation:

$$I = P \times A \times T, \qquad (2.11)$$

where *P* is human population, *A* consumption per capita, and *T* an index of environmental damage resulting from the technologies utilised in supplying each unit of consumption. The maximum amount of economic abuse that the environment can take, while still providing crucial ecosystem services, is defined by Daily and Ehrlich (1992) as the Maximum Sustainable Abuse (MSA). Given that there is a large amount of uncertainty associated with the impacts of human activities on natural capital stocks and services, determining the point of MSA is extremely difficult (Daily and Ehrlich, 1992). Returning the human-economic system to the point of MSA requires at least a reduction in the values for *P*, *A* and *T*.

More recently, the idea of carrying capacity has been encapsulated in the concept of ecological footprints (Wackernagel and Rees, 1996; Van den Bergh and Verbruggen, 1999; Wackernagel *et al.*, 1999, 2002; Rees, 2000; McDonald and Patterson, 2004). The objective is to translate all the ecological impact of human economic activity into the "area required to produce the resources consumed and to assimilate the wastes generated ... under the predominant management and production practices in any given year" (Wackernagel *et al.*, 2002, p.9266). If the ecological footprint overshoots the bioproductive land area available, then the carrying capacity of the area is in ecological deficit and the economic activity causing the ecological footprint is considered unsustainable (Neumayer, 2003).

2.3 Thermodynamic Interpretations of Sustainability

2.3.1 Statement of the Laws of Thermodynamics

The laws of thermodynamics, albeit among other principles, are central to the ecological economics perspective. According to the First Law of Thermodynamics, energy in an isolated

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[41] Vitousek *et al.* (1986) calculate that humans are consuming, co-opting and eliminating 40 percent of the basic energy supply of all non-human species and ecosystems.

system can neither be created nor destroyed. This law implies that for any open or closed system[42], the net amount of energy entering the system must equal the net increase in stored energy of that system.

The first law may be explained in terms of an energy conversion process, involving the burning of a lump of coal (Burness *et al.*, 1980; Baars, 1997). In its initial state, prior to combustion, the coal lump represents an embodiment of total energy. This total energy represents the sum of the internal, kinetic and potential energies of the molecules that constitute the coal lump. Following combustion, there is a difference between the embodied internal energy of the coal lump that was present in its initial state, P_1, and the embodied internal energy of the remaining ashes, that represent a second state, P_2. This difference represents a change in internal energy, P, which may be written as $P = P_2 - P_1$. In most energy conversion processes P is always negative in value, i.e. $P_1 > P_2$. Energy released in the transformation between P_1 and P_2 takes the form of heat transferred, Q_{12}, and work done, W_{12}, with the subscripts representing transfers between states 1 and 2 (Burness *et al.*, 1980; Ruth, 1993). Heat and work represent the flow of energy, while internal energy represents a stock (Kneese *et al.*, 1970; Georgescu-Roegen, 1971; Ayres and Nair, 1984). Given the conversion process described above, according to Burness *et al.* (1980), the first law establishes conservation of energy in a system as,[43]

$$P = Q_{12} - W_{12}. \tag{2.12}$$

The first law states that when a system undergoes a process, the energy transferred across the system boundary as either heat or work, is equivalent to the net change in the internal energy of the system. Thus, energy in any transformation process is not lost, but conserved, i.e. its form is simply altered (Ayres and Nair, 1984; Ruth, 1993).

The Second Law of Thermodynamics has been termed the 'entropy law' (Georgescu-Roegen, 1971). In order to use the second law in a quantitative sense, thermodynamicists introduce a working variable named 'entropy'. The second law has been expressed and utilised in different ways by different academic disciplines[44] (O'Connor, 1991). According to classical

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[42] Three types of system are recognised in thermodynamic analysis: (1) an isolated system, in which neither energy nor matter crosses the system boundary, (2) a closed system in which only energy, but not matter, crosses the system boundary, and (3) an open system, in which both matter and energy cross the boundary of the system (Faber *et al.*, 1987; Binswanger, 1993; Ruth, 1993).

[43] The changes in the coal's kinetic and potential energy are considered to be negligible.

[44] Binswanger (1993) lists five bodies of theory that utilise the concept of entropy. These include: (1) classical thermodynamic theory, which uses measurable macroscopic variables such as volume and temperature to describe isolated systems in a state of thermodynamic equilibrium, (2) statistical mechanics which describes the probabilistic behaviour of an ideal gas in an isolated system at a

thermodynamic theory, the entropy law describes, for an isolated system, the irreversible dissipation of (Gibbs free) energy – the result of which is an increase in the system's entropy (Prigogine, 1967; Georgescu-Roegen, 1971; Denbigh and Denbigh, 1985; Binswanger, 1993; Ruth, 1993). That is, if a system is initially in a low-entropy (ordered) state, its condition will tend to move involuntarily toward a state of maximum entropy (disorder). Under the first law, energy transfers across a system's boundary are represented as heat and/or work. Nothing prevents a process from being undone or reversed. The second law however dictates that every process that a system may undergo, be it physical, biological, technological or otherwise, can go in only one direction, and that the opposite process, which would return the system and its surrounds to their original states, is impossible.

According to classical thermodynamics, an increase in entropy, ds, of an isolated system between two states, S_1 and S_2, may be written as,

$$ds = \frac{Q}{T}, \tag{2.13}$$

where Q represents incremental and infinitesimal heat transfer, and T represents the absolute temperature of the system when Q is absorbed. Summation of all infinitesimal entropy increases, ds, allows for the specification of the total increase in system entropy, S, as,

$$S = S_2 - S_1. \tag{2.14}$$

In classical theory, the entropy law measures the exchange of heat[45] between systems that are considered to be in a state of thermodynamic equilibrium. Under a classical thermodynamic expression of the entropy term, reversible processes[46] may exist – characterised by infinitesimal changes in macroscopic variables which occur infinitely slowly (Denbigh and Denbigh, 1985; Faber, 1985; Binswanger, 1993). Nevertheless, all macroscopic processes operating in open

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microscopic level, (3) information or negentropy theories, concerned with the information content of messages and systems (Shannon and Weaver, 1949; Brillouin, 1962), (4) the theory of dissipative structures, which draws upon classical thermodynamics and statistical mechanics to describe the evolution of open systems toward higher complexity, in a state far from thermodynamic equilibrium (Prigogine, 1967), and (5) thermodynamic evolutionary theories in biology and ecology, that utilise both classical thermodynamics (Lotka, 1922), and the theory of dissipative structures (Odum, 1969).

[45] The presence of a temperature gradient, heat flow from a hotter to a colder body, is considered to be a prerequisite for the performance of work. Temperature, T, is a qualitative dimension of heat flow, Q (Denbigh and Denbigh, 1985; Binswanger, 1993).

[46] This implies that any transformations of a system during a process, measured as changes in macroscopic thermodynamic variables, can be completely undone (Binswanger, 1993). Reversible processes within isolated systems are theoretical ideals, ignoring friction, heat transfer across finite temperature boundaries, mixing, inelastic deformation or free expansion (Ruth, 1993).

and closed economic and ecological systems are irreversible. Several theorists therefore consider it inappropriate to use a classical thermodynamic expression of the second law to quantify entropy (Faber, 1985; Khalil, 1990; Binswanger, 1993; Ruth, 1993). Ruth (1993), for example, proposes that the entropy law for such systems, involving irreversible processes, must be written as,

$$S = \frac{Q}{T} \text{ with } S > 0, \tag{2.15}$$

where S denotes a change in system entropy, Q heat transfer to, or from, the system, and T the absolute temperature of the part of the system to which heat Q is transferred.

Prigogine (1967, 1973) and Prigogine *et al.* (1972) have reformulated and extended the classical thermodynamic, and statistical mechanics[47], conceptions of entropy. Prigogine's work provides an explanation for the irreversible processes associated with open systems. According to Prigogine's (1967) theory of non-equilibrium thermodynamics, entropy change, ds, may be reformulated as,

$$ds = ds_e + ds_i, \tag{2.16}$$

where ds_e represents the flow of entropy resulting from exchanges with the environment of the system[48], and ds_i the production of entropy as a consequence of irreversible processes inside the system. The term ds_e may be either positive or negative in value – when negative, entropy inside the system, ds_i, will decrease (Prigogine, 1967; Binswanger, 1993). In such a case, according to Binswanger (1993), one of three distinct forms of entropic interaction between the system and the environment may exist: (1) entropy is increasing inside the system at a rate faster than the flow of negative entropy to the environment i.e. $-ds_e < ds_i$ with $ds > 0$, (2) the flow of negative entropy to the environment equals the production of entropy within the system, so the entropy level of the system remains constant i.e. $-ds_e = ds_i$ with $ds > 0$, or (3) the entropy of the system is decreasing, but the flow of negative entropy to the environment exceeds the production of entropy within the system, resulting in a system moving away from

[47] Statistical mechanics suggests that systems do not tend to go into states that are less probable than those they are already in (Binswanger, 1993). Statistical mechanics, unlike classical thermodynamics, acknowledges that systems may be in non-equilibrium states, providing a microscopic basis for irreversibility (Prigogine, 1973; Harrison, 1975; Wicken, 1988).

[48] Under Prigogine's theory this flow may, in the case of an isolated system, be zero i.e. ds_e=0. Thus ds would not only equal ds_i, but would be positive in value, or zero if the system is in thermodynamic equilibrium (Prigogine, 1967; Binswanger, 1993).

thermodynamic equilibrium i.e. $-ds_e > ds_i$ with $ds < 0$. In this way, Prigogine (1967) defines the second law for irreversible processes, including open systems, as $ds_i > 0$.

It is the third form of entropic interaction noted above that is often used in explaining the evolution of open systems towards a state of higher complexity (Prigogine, 1967; Binswanger, 1993; Ruth, 1993). Open systems, far off thermodynamic equilibrium, may only establish and sustain their low entropy states by creating flows of negative entropy to their environment via the dissipation of energy and matter (Prigogine, 1967; Glansdorff and Prigogine, 1971; Prigogine *et al.*, 1972). Such systems, following Schrodinger (1944), are termed 'dissipative structures'.[49] The flow of negative entropy from a dissipative structure always results in an increase in the entropy of the system's environment.

The Third Law of Thermodynamics further constrains the interplay between heat, temperature and entropy. The third law states that as absolute zero (approximately -273˚C) is approached, the extraction of energy from a system or its environment becomes increasingly more difficult.

2.3.1.1 The First Law of Thermodynamics and Sustainability

During the 1960s and 1970s, environmental economists employed the first law (and the mass conservation principle) to characterise the relationship between the scale of economic activity and environmental quality[50,51] (Barbier, 1989; Common, 1995). Ayres and Kneese (1969), for example, utilise the so-called 'materials balance principle' in their interpretation of the first law. This principle implies that, barring accumulation in the production process, all materials extracted or harvested from the environment for use in economic activity, must ultimately, in mass terms, be returned to the environment in the form of unwanted products and wastes. Material and energy residues generated by the economic system and emitted into the environment as pollution or waste must therefore (by assuming no accumulation) be equal to those initially extracted from the environment (Ayres and Kneese, 1969; Kneese *et al.*, 1970; Victor, 1972a).

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[49] Thermodynamic potentials between systems and their environment, as measured by temperature, concentration or pressure gradients, must be sufficiently large to permit flows of negative entropy, $-ds_e$, to the system environment. When such thermodynamic potentials are exceeded, the system may move to a new state further from thermodynamic equilibrium, where new structures may evolve to dissipate higher levels of negative entropy (Prigogine *et al.*, 1972; Prigogine and Stengers, 1984; Binswanger, 1993).

[50] Strictly speaking, the First Law of Thermodynamics only applies to the conservative nature of energy transformations. In Section 2.3.1.1, however, the term 'first law' is used to collectively refer to both the energy and mass conservation principles.

[51] Including studies by Ayres and Kneese (1969), Kneese *et al.* (1970), Converse (1971), Victor (1972), Cumberland and Korbach (1973), d'Arge and Kogiku (1973), Nijkamp (1977), Ayres and Noble (1978), Kneese and Bower (1979), and Johnson and Bennett (1981).

From these first law interpretations (energy and mass conservation), arose a conceptualisation of the economy used by many ecological economists. The economy is seen as an open system embedded within the global biophysical system – Gilliland (1977) was amongst the first to formally propose this theoretical schema. The economic system is therefore viewed as being nested within the greater ecological system, ultimately transforming inputs of low entropy energy (e.g. fossil fuels) and matter (e.g. minerals) into outputs of highly degraded entropy, like manufactured goods and emissions, that flow into the environment (Colby, 1991; Ekins, 1994; Reid, 1995; Wetzel, 1995).

The biophysical (thermodynamic) view of sustainability leads to an appreciation of three important constraints on the sustainability of the economic system, as identified by Patterson (2002b) among others:

- *Resource (input) constraints.* The physical growth of the economic system depends on the continuous flow of materials and energy inputs into the system from the biosphere. Many resources are clearly finite given first law considerations and are therefore depletable, e.g. fossil fuels, minerals. If the stock of these resources is depleted or degraded, economic growth cannot be sustained indefinitely;
- *Waste/residual (output) constraints.* In a physical sense, sustainability of the economic system depends on the ability of the biophysical environment to absorb and purify wastes/residuals produced by the economy, i.e. the economy relies on the sink functions of the biophysical environment, such as efficient purification and absorption of wastes and emissions. Critical thresholds exist, however, beyond which the environment may not cope with ever increasing wastes, which lead to local scale impacts like eutrophication through to global impacts like climate change;[52]
- *Size/scale of the economic subsystem.* In a physical sense the embedded economic subsystem cannot exceed the size of the biosphere space which it occupies. For example, Vitousek *et al.* (1986) estimate that the economy has appropriated 40 percent of the net primary productivity of the terrestrial biosphere. The ultimate physical limit cannot exceed 100 percent, and to provide a safety margin, it has been argued that a

[52] One possibility to reduce flows of wastes/residuals into the biophysical environment from the economy is to recycle materials (Biancardi *et al.*, 1993, 1994, 1996; Khalil, 1994; Mansson, 1994). Authors such as Georgescu-Roegen (1976), Kummel (1994) and Converse (1996) however argue that 100 percent recycling is a physical impossibility. The Second Law of Thermodynamics, for example, tells us that energy cannot be re-used or recycled, in the sense that once, say, a piece of coal is burnt, the same amount of 'useful' energy cannot be extracted from that piece of coal. Furthermore, the costs of recycling material are likely to become prohibitively high as the recycling rate tends to 100 percent (Neumayer, 2003).

limit of 80 percent is more realistic. Any increase in scale, as measured in terms of economic production and consumption, will also result in a corresponding increase in the required quantity of environmental material and energy inputs. In turn, increased throughput of materials and energy resources through the economy will lead to a corresponding increase in the pollution loading placed on the environment (Barbier, 1989; Klaassen and Opschoor, 1991; Victor, 1991).

In summary, the capacity of the environmental system to provide resources and assimilate waste governs the maximum sustainable physical scale of the economy. As Daly (1994) argues, according to the first law, economic growth can only occur at the expense of the environment. Any increase in the physical dimensions of the world economy, as a subsystem of physical Earth, therefore implies a corresponding decrease in the physical size of the environment, since the Earth has only a finite mass. Accordingly, Kamien and Schwartz (1982) have argued that the first law thus imposes an upper limit on the extent to which manufactured capital can substitute for natural capital as a factor of production. Ecological economists, such as Goodland and Daly (1993), therefore suggest an economic policy goal of minimisation of energy and material throughput in order to maintain the physical sustainability of the economic system.

2.3.1.2 The Second Law of Thermodynamics and Sustainability

While many economists interested in thermodynamics have concentrated on the first law, theorists such as Georgescu-Roegen (1971), Daly (1977) and Perrings (1987) have insisted that it is the second law which is of most significance. Georgescu-Roegen (1971, 1976, 1977a) has argued that the entropy law can be applied to the transformations of energy and matter[53] that occur within the economic system. The argument follows that such transformations always involve the degradation of high quality energy and matter (low entropy) forms of higher economic value (highly organised materials and energy), to low quality (high entropy) forms of lower economic value (highly disorganised materials and energy) (Georgescu-Roegen, 1971; Daly, 1973, 1991a; Perrings, 1987; Barbier, 1989; Victor, 1991). The second law implies that complete recycling of economic wastes and residuals is a physical impossibility (Georgescu-

[53] Georgescu-Roegen (1977a, 1977b, 1977c, 1979b) has formulated a 'fourth law' of thermodynamics, which he argues governs all economic activity. He argues that "matter matters too" (1979, p.1039) and therefore in a closed system, such as biosphere, "material entropy must ultimately reach a maximum" (1977b, p.269). The notion of material entropy has however been hotly debated (see, for example, Bianciardi *et al.* (1993, 1994, 1996), Khalil (1994), Kummel (1994), Mansson (1994), Converse (1996), and Corning (2002)). At the crux of the debate is the assumed isomorphism between energetic order and physical order.

Roegen, 1971, 1976; Booth, 2004).[54] At each successive stage of an economic process, the entropy of matter and energy engaged within that process increases in an irreversible manner, making that matter and energy progressively less useful in future economic activity[55] (Daly, 1987; Barbier, 1989, 1990; Klaassen and Opschoor, 1991; Victor, 1991). Taking the longest of long views, the second law acts as the ultimate regulator of all activity, be it economic or otherwise; thus sustainability is inherently unachievable, even theoretically meaningless (Victor, 1991).

Daly (1991a, 1992, 1994) takes a more pragmatic approach in his application of the second law to sustainability issues. He argues for a steady state economic system based on the thermodynamic constraints that the first and second laws impose on the overall sustainable scale of macro-economic activity. Daly (1973, p.98) defines the desirable steady state economy as "an economy in which the total population and the total stock of physical wealth are maintained constant at some desired levels by a minimal rate of maintenance throughput (i.e. by birth and death rates that are equal at the lowest feasible level, and by physical production and consumption rates that are equal at the lowest feasible level)".

Daly (1987, 1991a, 1992, 1994) advocates that the achievement of economic sustainability will require a decrease in the current rate of matter and energy throughput into the economic system, such that the overall scale of the economy corresponds with the carrying capacity of the global environment. Descaling the economy will require zero economic growth and near zero human population growth (Daly, 1991a, 1992; Turner, 1993; Ekins, 2000). To this end, Daly (1991b) provides four operational principles for economic sustainability: (1) limit the scale of human, including population and macro-economic, activity to a level which is within the carrying capacity of the Earth; (2) technological progress should be efficiency increasing rather than throughput increasing; (3) the rate of harvest of renewable resources should not exceed the regeneration rate of those resources, and the generation of economic waste emissions should not exceed the waste assimilating capacity of the environment; and (4) non-renewable resources should be exploited, but at a rate equal to the creation of renewable substitutes.

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[54] Georgescu-Roegen (1971, 1976) asserts that complete recycling of matter is impossible in a closed system. This assertion has been challenged, as part of the debate on Georgescu-Roegen's proposed fourth law of thermodynamics, by several authors (see, for example, Bianciardi *et al.* (1993, 1994, 1996), Khalil (1994), Mansson (1994)). Bianciardi *et al.* (1993, 1994, 1996) and Khalil (1994, 1995, 1997), for example, argue that Georgescu-Roegen's assertion cannot be theoretically grounded as a physical principle. Nevertheless, they also point out that complete recycling is practically impossible, "[complete recycling] would involve a tremendous increase in the entropy of the environment, which would not be sustainable for the biosphere" (Bianciardi *et al.*, 1996, p.195).

[55] Many neo-classical economists assume the possibility of continual resource recycling in their analysis of sustainable economic growth (see, for example, Maler (1974)).

Norgaard (1986) is critical of Daly's argument in favour of a low throughput economy. Norgaard (1986) argues that since increasing entropy is not simply just an ill effect of human activity, but also a natural process, there is no critical level below which global entropy will not increase. Daly (1987, 1991a, 1992) ignores or glosses over the Earth's annual influx of solar energy, which potentially could fix energy into Earth matter, countering any entropic degradation brought on by natural or economic processes (Norgaard, 1986; Klaassen and Opschoor, 1991). Norgaard (1986) argues that we could make far more efficient use of solar flux than we do now, offsetting any entropy increases effected by economic activity.

2.4 Key Principles for Assessing Auckland Region's Sustainability

This Section presents eight theoretical principles for progressing toward sustainable development. The principles, which are described in detail in Table 2.1, are:

- *Principle 1* Maintain total capital stock within the limits of critical natural capital ('Weak Sustainability')
- *Principle 2* Substitute non-renewable with renewable natural capital
- *Principle 3* Maintain human activity within the carrying capacity of the environment
- *Principle 4* Maintain environmental life support services
- *Principle 5* Maintain the assimilative capacity of the environment
- *Principle 6* Use natural capital efficiently
- *Principle 7* Minimise material and energy throughput through the economy
- *Principle 8* Maintain the resilience of the ecological-economic system

These principles are based on the economic, ecological, and thermodynamic interpretations of sustainability outlined in the preceding Sections. They advocate the theoretical means by which the concept of sustainability might be operationalised or implemented in the Auckland Region. A rationale for each principle is provided, along with supporting literature and theorists, and a guide to its application in relevant subsequent thesis Chapters and Sections. Connections and interdependencies between the principles are described by Figure 2.3.

Table 2.1 Theoretical Principles for Sustainable Development and their Application in this Thesis

	Principle 1: Maintain[1] total capital stock within the limits of critical natural capital ('Weak Sustainability')	Principle 2: Substitute non-renewable with renewable natural capital
Definition	The total capital stock, including natural, manufactured and social[2] capital must be maintained inter-generationally. Substitutability between different forms of capital is permissible.	In economic processes, substitute non-renewable resources with renewable resources.
Rationale	• The provision of a constant stock of capital ensures that the economic welfare of current and future generations is met.	The greater use of renewables: • inherently involves the continuous recycling of mass, which has two key advantages: (1) wastes/residuals are reused, thereby reducing the environmental loading by these wastes/residuals, (2) the stocks of renewable resources are not depleted, as they are being continuously regenerated by these recycling processes. This is not the case with renewable resources • reduces the pressure placed on the depletion of non-renewable resources
Key Supporting References	Solow (1974, 1986), Hartwick (1977, 1978), Holling (1986, 1995), Perrings (1987, 1991), Pearce and Turner (1990), Daly (1991a, 1994), Victor (1991), Ehrlich (1994), Jansson and Jansson (1994), Costanza and Patten (1995), Munasinghe and McNeely (1995), Ekins (2000, 2003), Pearce and Barbier (2000), Neumayer (2003)	Clark (1976), Baumol and Oates (1988), Pearce and Turner (1990), Turner (1993), Pearce and Barbier (2000), Booth (2004)
Application of the Principle in this Thesis	• Chapter 4: Establish framework for static flow analysis of economic and biophysical flows, including depletion and formation of manufactured and natural capital stocks • Chapter 5: Establish flow estimates of the depletion and formation of manufactured capital stocks • Chapters 6 & 7: Establish flow estimates of the depletion and formation of natural capital stocks e.g. water, energy, land, ecosystem services, minerals, forestry, fisheries, etc. • Chapter 10: Identify key drivers of change that influence Auckland Region's manufactured and natural capital stocks • Chapter 11: Conceptualise the dynamics of the interdependencies between Auckland's manufactured and natural capital stocks. Scenario modelling of policy options that influence natural capital stocks	• Chapter 11: Dynamic modelling of Auckland Region's ecological-economic interactions, including the possibility of substituting non-renewable for renewable resources. Scenario modelling of policy options, including the implications of substituting non-renewable with renewable natural capital

Notes:

1. The term 'maintain', as used in the first five principles, refers to maintenance of both qualitative and quantitative aspects.
2. While it is acknowledged that the total capital stock includes social (i.e. human, cultural, *etc.*) capital, these forms of capital receive only cursory consideration in the remainder of this thesis.

Table 2.1 Theoretical Principles for Sustainable Development and their Application in this Thesis (Continued)

	Principle 3: Maintain human activity within the carrying capacity of the environment	Principle 4: Maintain environmental life support services
Definition	Human activity must be maintained within the supportable bounds of the environment. Carrying capacity refers to the maximum number of people that the environment can support, without reducing its ability to support future generations. Carrying capacity implicitly allows for the continued co-existence of other life forms. The unique ability of humans to appropriate resources from elsewhere, and smooth out economic or environmental fluctuations, must also be taken into consideration when determining carrying capacity.	Environmental life support services must be maintained. Such services encompass those biogeochemical processes and ecosystem services functions essential for all forms of life.
Rationale	Maintenance of human activity within the carrying capacity of the environment • recognises the finite capacity of the environment in providing natural resources and ecosystem services, assimilating waste residuals, absorbing stochastic environmental shocks or disturbances, and in providing life support services • recognises that exceeding carrying capacity could irreversibly degrade the stock of natural capital	Environmental life support services • provide refuge and reproduction habitats that contribute to the *in situ* conservation of biological, genetic and evolutionary processes (de Groot *et al*., 2002) • provide production functions that enable conversion of biomass and energy into carbohydrate through the process of photosynthesis, in turn providing food for human consumption (de Groot *et al*., 2002) • provide opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetic experience (de Groot *et al*., 2002) • protect the biosphere from risk of collapse or decline • protect the biosphere's self-organising and species-supporting capacity • cannot be replicated, or substituted for, by other forms of capital • possess intrinsic value in their own right
Key Supporting References	Holdren and Ehrlich (1974), Ehrlich and Ehrlich (1981), Daily and Ehrlich (1992), Holdren *et al*. (1993), Ehrlich (1994), Wackernagel and Rees (1996), Wackernagel *et al*. (1999, 2002), Rees (2000)	Barbier (1989, 1990), Folke *et al*. (1989), Folke (1991), de Groot (1992), Berkes and Folke (1994), Costanza *et al*. (1997), Folke *et al*. (1997), Ekins (2000, 2003), de Groot *et al*. (2002)
Application of the Principle in this Thesis	• Chapter 8: Estimate Auckland Region's Ecological Footprint using an input-output approach. This includes estimation of land, energy and CO_2 resource/residual footprints for the region	• Chapter 4: Establish framework for analysis of ecological interdependencies between biosphere stocks and processes that operate within the Auckland Region • Chapter 6: Estimate biophysical waste/residual fluxes associated with economic activity on an industry- and economy-wide basis • Chapter 7: Assess the value that ecosystem services, including processes providing life support, make to the Auckland regional economy using a TEV approach. Estimate the mass flux associated with biogeochemical cycing in the Auckland Region • Chapter 10: Identify the key drivers of human controlled change that influence Auckland Region's environmental life supporting capabilities • Chapter 11: Dynamic modelling of biophysical waste/residual fluxes associated with economic activity • Appendix B: Dynamic modelling of global biogeochemical processes

Table 2.1 Theoretical Principles for Sustainable Development and their Application in this Thesis (Continued)

	Principle 5: Maintain the assimilative capacity of the environment	Principle 6: Use natural capital efficiently
Definition	The assimilative capacity of the environment must be maintained. Assimilative capacity refers to those biogeochemical processes and ecosystem services that ameliorate the impacts of residuals (i.e. pollution, wastes and emissions) generated from human activities. Cleansing of sudden stochastic events, decomposition of biological materials and the like are similarly included.	The efficient use of natural capital in economic production requires minimisation of resource input per unit of output. Similarly, the efficient use of natural capital in human consumption activities requires maximisation of economic welfare per unit of natural resource input. The most efficient processes may involve autocatalytic feedbacks, giving the maximum power per unit of energy input (Odum, 1996).
Rationale	The assimilative capacity of the environment • provides regeneration functions that maintain a healthy environment providing clear air, water and soil, and biological control services • contributes to the continued regeneration of renewable resources • protects the biosphere from risk of collapse or decline	Using natural capital efficiently • preserves stocks of natural capital for future generations • provides opportunities for enlargement of the natural capital stock • reduces economic waste associated with the use of natural capital, resulting in a cleaner environment and higher quality of life support systems • reduces the potential impact on the regeneration rates of other forms of natural capital
Key Supporting References	de Groot (1992), den Elzen *et al*. (1995), Costanza *et al*. (1997), Ekins (2000, 2003), de Groot *et al*. (2002)	Herfindahl and Kneese (1974), Dasgupta and Heal (1979), Baumol and Oates (1988), Young (1992), Turner (1993), Bartelmus (1994), Pearce and Barbier (2000), Booth (2004)
Application of the Principle in this Thesis	• Chapter 7: Assess the value that ecosystem services make to the Auckland Region using a TEV approach, including processes assimilating residuals and absorbing natural shocks/perturbations. Estimate the mass flux associated with biogeochemical cycing in the Auckland Region • Chapter 10: Identify the key drivers of human induced change that influence Auckland Region's assimilative capacity • Appendix B: Dynamic modelling of key biogeochemical cycles, including assimilative processes	• Chapter 4: Establish framework for static flow analysis of economic and biophysical flows • Chapter 5: Estimate gross output, gdp and bot on an industry basis. This information will be used in conjunction with biophysical information to estimate eco-efficiency indicators • Chapter 6: Estimate biophysical flows associated with economic activity on an industry- and economy-wide basis • Chapter 6: In conjunction with the economic and biophysical fluxes established above, derive eco-efficiency on an industry- and economy-wide basis e.g. resource input per $ output/gdp, residual outputs per $ output/gdp, total embodied resource requirements per total embodied dollars generated, total embodied residuals output per total embodied dollars generated • Chapter 8: Estimate Ecological Footprint of the Auckland Region and establish level of interdependence with other New Zealand regions

Table 2.1 Theoretical Principles for Sustainable Development and their Application in this Thesis (Continued)

	Principle 7: Minimise material and energy throughput through the economy	**Principle 8: Maintain the resilience of the ecological-economic system**
Definition	Economic throughput of materials and energy must be curtailed inter-generationally. Throughput requires the extraction/harvest of natural resources, manufacture or consumption of an economic product and the generation of residuals/wastes.	The resilience of the ecological-economic system must be maintained so that it can absorb stresses and shocks without fundamental change i.e. the organisational structure, function and patterns of behaviour of the system must be retained.
Rationale	Minimisation of material and energy throughput • provides a buffer of natural capital for protection against stochastic environmental change • ensures that materials and energy are available over and above those required for carrying capacity, life support and so on. This provides a reserve for currently unanticipated future requirements i.e. is prudently pessimistic, or precautionary, to accommodate unforeseen applications of the various forms of capital • ensures that the scale of human activity remains not only within the bounds dictated by the finiteness of the biosphere, but also provides a reserve • recognises, in accordance with the first law of thermodynamics, that all material and energy inputs into the economy must ultimately (i.e. assuming no storage) equate to the quantity of residual wastes 'spat out' into the environment • recognises, in accordance with the second law of thermodynamics, that increased throughput accelerates the entropic degradation of useful matter and energy	The resilience of the environment • protects the biosphere from risk of stochastic collapse or decline • protects the biosphere from risk of human-induced perturbations that may result in collapse or decline • protects the economy by allowing recovery from the negative effects of environmental and human-induced shocks
Key Supporting References	Daly (1973, 1991a, 1992), Ekins (2000, 2003), Pearce and Barbier (2000)	Holling (1973, 1986), Common and Perrings (1992), Odum (1996), Levin *et al*. (1998)
Application of the Principle in this Thesis	• Chapter 4: Establish framework for static flow analysis of economic and biophysical flows • Chapter 6: Benchmark material throughput, in mass terms, using an Auckland Region PIOT • Chapter 11: Dynamic modelling of Auckland Region material throughput. Scenario modelling of policy options, including the implications on material throughput	• Chapter 11: Test out the resilience (i.e. risk of collapse) of the Auckland ecological-economic system to shocks resulting from possible future human-induced growth scenarios • Appendix B: Test out the resilience (i.e. risk of collapse) of the global ecological-economic system to stochastic natural shocks by the incorporation of random environmental change into the modelling framework

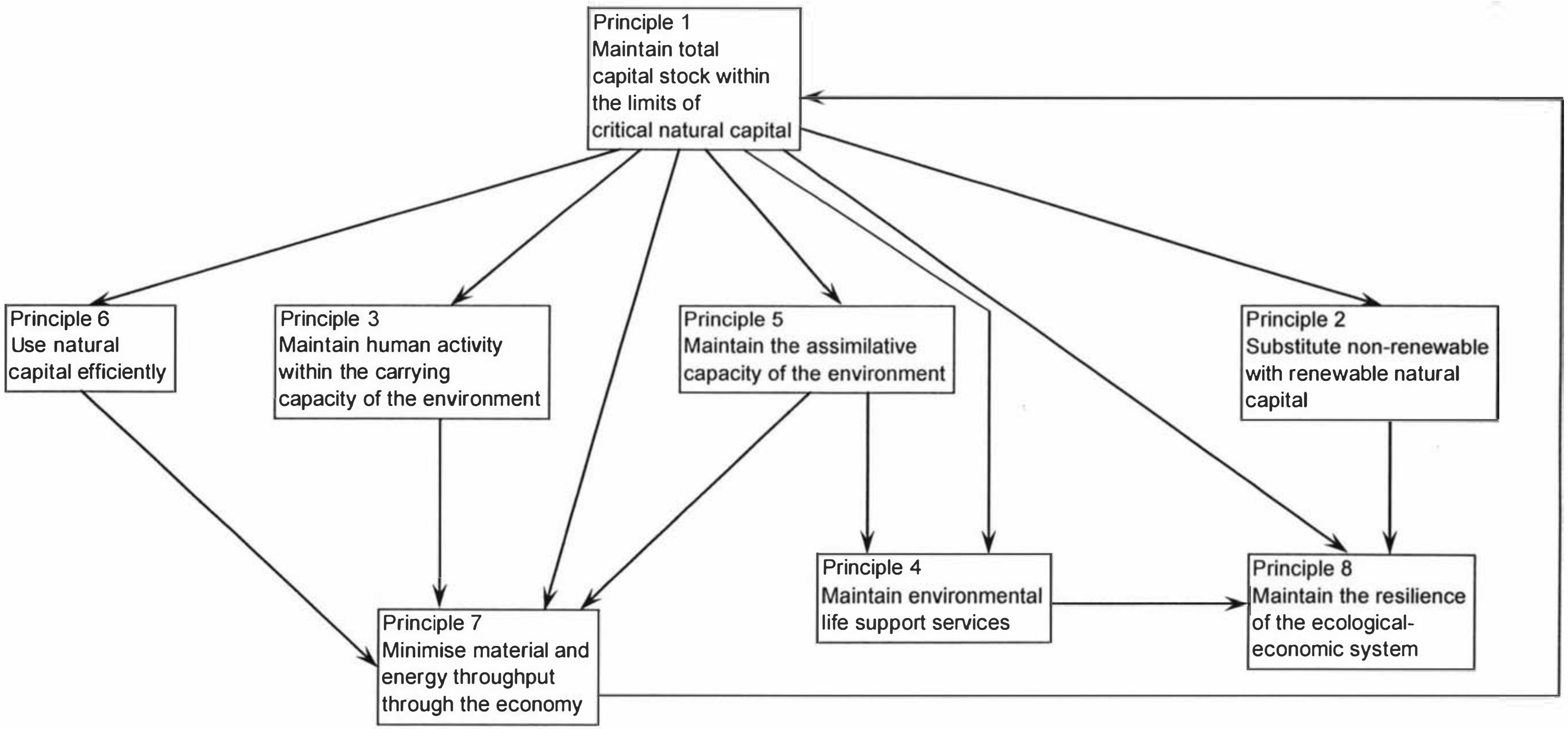

Figure 2.3 Interrelationships between Key Principles of Sustainability

Chapter Three

Approaches to Urban Development and Sustainability

This Chapter narrows the focus of the thesis to urban sustainability and the way different disciplines conceptualise urban growth and development. The first part of this Chapter critically reviews the traditional approaches to the question of urban dynamics, and argues that these approaches reflect the 'Human Exemptionalism Paradigm' (HEP)[56] which dominates the social sciences and humanities. Under this paradigm it is argued that human beings, by virtue of culture and human ingenuity will overcome all social and environmental problems confronting humankind. The remainder of this Chapter outlines new and emerging ecological approaches to urban sustainability and development which reflect the so-called 'New Ecological Paradigm' (NEP).[57] These approaches acknowledge the ecological and the thermodynamic realities of (urban) growth as alluded to in Chapter 2, i.e. that cities depend on the biophysical environment for their survival and functioning, cities are ecosystems in the sense that they are complex networks of energy and material flows, and cities are subject to ecological limits like any ecological system.

3.1 The Human Exemptionalism Paradigm

Emerging environmental problems in the late 1960s and early 1970s focused society's attention on the reality of biophysical constraints to human progress. Consequently, many sociologists began to examine the relevance of the environment to sociology (Buttel, 1997; Dunlap, 2002). In seeking to understand whether environmental sociology was sufficiently distinctive to be considered a new field, two sociologists in the 1970s, William Catton and Riley Dunlap, noticed that despite the apparent diversity in the main competing theoretical sociological perspectives (e.g. functionalism, conflict theory, symbolic interactionism and so on) a fundamental anthropocentrism underpinned them all (Catton and Dunlap, 1978; Buttel *et al.*, 2002).[58] Catton and Dunlap (1978) argued that mainstream sociology had largely ignored the biophysical

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[56] Catton and Dunlap (1978) originally termed this perspective the 'human exceptionalism paradigm' as it emphasises the exceptional characteristics of the human species by virtue of culture, language and technology. In order, however, to acknowledge that they were not questioning these characteristics, but rather the assumption that these characteristics exempted humans from ecological constraints, they later changed the term to 'human exemptionalism paradigm' (Dunlap, 1997, 2002).

[57] Catton and Dunlap (1978) originally labeled this paradigm the 'new environmental paradigm', but later revised this to the 'new ecological paradigm' as it seeks to emphasise the ecological base of human society (Dunlap, 1997, 2002).

[58] This also applies to the sociological perspectives that have since followed or were at the time in their infancy i.e. rational choice and exchange theory, ethnomethodology, phenomethodology, feminism, post-structuralism and post-modernism.

environment. Drawing on Thomas Kuhn's (1962) theory of scientific revolutions, as well as sociologists like Ritzer (1975), they argued that certain sociological traditions and assumptions constituted a paradigm which they called the Human Exemptionalism Paradigm (Catton and Dunlap, 1978; Dunlap, 1997, 2002; Bell, 2004).[59]

3.1.1 Assumptions of the Human Exemptionalism Paradigm

Catton and Dunlap (1978) and Dunlap (2002) outline four primary assumptions that they believe not only blinkered contemporary sociologists to the social implications of ecological issues, but predisposed them to the optimism of the prevailing worldview, i.e. the assumption that there were no resource scarcities or other biophysical constraints on society's infinite growth and progress. These HEP assumptions are (1) humans, by virtue of their cultural heritage, are unique among all animal species; (2) social and cultural factors (including technology) can vary almost infinitely, changing far more rapidly than biological traits, and are therefore the primary determinants of human affairs. Many human differences are socially conditioned rather than genetic and can therefore be changed or eliminated if undesirable; (3) the crucial context for human affairs is the social and cultural environment, rendering the ecological environment largely inconsequential; and (4) cultural accumulation means that technological and social progress can continue without limit, making all social problems ultimately solvable. Catton and Dunlap (1978) argue that this optimistic worldview has been undoubtedly fostered by Western thought, i.e. that human ingenuity, in particular the creation of technology, creates unlimited opportunities to continue human progress. Accordingly, sociologists have not perceived the possibility of a future of genuine scarcity, but have instead ignored concepts such as carrying capacity, scientific laws such as conservation of mass and energy, and the principle of entropy (Catton and Dunlap, 1978).

In the remainder of this Section five major schools of thought on urban environments are discussed. Because of their inherent anthropocentrism all five may be characterised as belonging to the HEP worldview. Urban sociology examines social order in the urban environment, urban ecology studies how people arrange themselves within an urban environment, urban geography looks at the physical location of urban areas, urban psychology examines people's experiences of the urban environment, and urban political economy

[59] Ritzer (1975, p.7) described a paradigm as "a fundamental image of the subject matter" and "the broadest unit of consensus" within a discipline. Warner (1997, p.193) defines a paradigm as "a way of seeing the world, a representation, picture or narrative of the fundamental properties of reality". Dunlap (2002) believes that the HEP represented the largely consensual opinion of the sociologists of the time, i.e. that a consideration of society's ecological base is irrelevant to an understanding of modern industrial societies, and for this reason the HEP constitutes a paradigm.

examines the urban dynamics resulting from political and economic decisions and trends.[60] All examine the urban environment from diverse perspectives, but share a common underlying anthropocentrism.

3.1.2 Classical Sociological Theory

Late nineteenth century sociologists were particularly interested in the urban upheaval resulting from the capitalistic processes of the Industrial Revolution. They were pessimistic about urban life, envisaging the city as a dangerous, dirty and undesirable place where the traditional values of social life disintegrated. European sociologists such as Karl Marx (1818 – 1883), Friedrich Engels (1820 – 1895), Ferdinand Tönnies (1855 – 1936), Emile Durkheim (1858 – 1917), Georg Simmel (1858 – 1918) and Max Weber (1864 – 1920) typified this thinking.

Karl Marx and Friedrich Engels collaborated closely on their work examining the conflict between the social classes during the height of the Industrial Revolution (Frey and Zimmer, 2001; Kleniewski, 2002). They argued that the social institutions of family, religion and the political system were founded on the economic structure of society. Marx and Engels viewed the rise of urban settlements as signalling a transition from barbarism to civilisation, arguing that urban problems such as poverty and unemployment are the fault, not of the individual, but of the capitalist structure (Kleniewski, 2002; Thorns, 2002; Bounds, 2004). They contended that the social evolution of humans would not be complete until revolution transformed into socialism.

In 1887, Ferdinand Tönnies published *Gemeinschaft and Gesellschaft*, in which he described two contrasting types of social life (Tönnies, 1963/1887; Flanagan, 1993; Saunders, 2001; Paddison, 2001; Kleniewski, 2002; Thorns, 2002; Bounds, 2004). Gemeinschaft, or 'community', is characteristic of the country village where people work together for the common good, united by ties of family and neighbourhood. Gesellschaft, or 'association', is characteristic of urban settlements, where social life is a 'mechanical aggregate' distinguished by disunity, individualism and selfishness. The meaning of existence shifts from the group to the individual with family and neighbourhood ties of little significance. Tönnies believed that,

[60] These schools of thought encompass Western thinking on the city as recorded over the last 160 years. By no means is this coverage presented here complete, nor are the summaries of the contributions made by key authors; rather the focus is on capturing the central themes of each school. Other viewpoints on the city, as based on the HEP, include urban planning (e.g. Ebenezer Howard (1965), Jane Jacobs (1961, 1970, 1984), Herbert Gans (1962, 1982)), urban design and form (e.g. Le Corbusier (1929[1924], 1967[1935]), Frank Lloyd Wright (1958), Paolo Soleri (1969)) and the history of the city (e.g. Lewis Mumford (1961)).

when viewed over time, urbanisation in European history revealed a gradual replacement of Gemeinschaft by Gesellschaft as the dominant way of life (Macionis and Parrillo, 1998).

Emile Durkheim (1964/1893), in *The Division of Labor in Society*, considered urban social structure, developing a model of two contrasting types of social order, namely 'mechanical solidarity' and 'organic solidarity' (Flanagan, 1993; Kleniewski, 2002; Thorns, 2002; Bounds, 2004). Mechanical solidarity describes the social unity that is brought about by a commonality of beliefs, customs, rituals and symbols, and is characteristic of many rural and primitive self-sufficient societies. By contrast, organic solidarity refers to the social order of modern industrial societies, which are constructed on individual differences and an advanced division of labour – distinguished by specialisation of occupation. While Tönnies viewed the urban settlement as undermining of the very fabric of society, Durkheim viewed such settlements as giving rise to greater freedom of choice for the individual, creating a liberating form of social cohesion based on mutual interdependence (Macionis and Parrillo, 1998).

Georg Simmel (1964/1905) focused on the urban experience, in particular the social psychology of urban dwellers. Simmel viewed the urban experience as a constant bombardment of nervous stimuli with the individual continually discriminating between stimuli to avoid being overwhelmed. As a result, he believed that urban dwellers became more rational, calculating, emotionally reserved and intellectual (Flanagan, 1993; Kleniewski, 2002; Popenoe and Michelson, 2002; Bounds, 2004). Simmel, like Durkheim, acknowledged the existence of an advanced economic division of labour, with social order based on the interplay of specialists. He argued that money played a pivotal role as a universal means of exchange, driving the shift from Gemeinschaft to Gesellschaft (Macionis and Parrillo, 1998). He further believed that the urban environment held the potential for great personal fulfilment, but feared that feelings of alienation and loss of individuality may ultimately override this potential (Flanagan, 1993; Wirth-Nesher, 2001).

Max Weber (1966) undertook a survey of various urban areas in Europe, the Middle East, India and China (Macionis and Parrillo, 1998; Orum and Chen, 2003). Weber argued that any theory that studied the sociology of urban settlements in only one part of the world, at any one point in time, was inadequate. In 1921 Weber published *Die Stadt* ('The City') in which he defined the requirement of a full urban community: a predominance of trade or commercial relations, such as a market; a court and at least partially autonomous law of its own; at least partial political autonomy; a protective fortification or military self-sufficiency; and a means of association or social participation for individuals (Macionis and Parrillo, 1998; Bounds, 2004). Weber viewed the urban environment as a potentially positive and liberating force in human life, but felt that the Industrial Revolution had brought about a loss of military and political autonomy, such that people no longer felt a sense of allegiance to the urban community (Flanagan, 1993). As a result, Weber did not hold out much hope for future urban environments.

From Classical Theory to Modern Research

The major contribution of the early urban theorists was their identification of the urban environment as an object worthy of study (Macionis and Parrillo, 1998). All viewed urban settlements as increasing the potential for self-actualisation, and they emphasised rationality, individuality and an advanced division of labour. Tönnies, Simmel and Durkheim emphasised social order, social cohesion, community ties and social differentiation, while Marx, Engels and Weber stressed social, economic and political power relations as prime determinants of the urban experience (Kleniewski, 2002).

There are several key criticisms of the early sociologists' thinking on the city. Firstly, they tended to focus on the sociological extremes of urban settlements, proposing dichotomous perspectives with the perceived future endpoints dominating their discourse (Thorns, 2002). Secondly, they all had an implicit bias in favour of rural life, with a predominant view of the urban environment as a place where community was lost and feelings of alienation developed (Thorns, 2002). The idea that urban relationships were impersonal, lonely, indifferent and anonymous has since been refuted by numerous studies which have revealed that city life does not preclude the existence of strong family, neighbourhood and friendship ties (Whyte, 1943; Bell and Boat, 1957; Greer, 1962; Bruce, 1970; Suttles, 1972; Fischer, 1975; Street *et al.*, 1978). Thirdly, the classical theorists' hypothesis of urban malaise has been questioned by subsequent research (Verbrugge and Taylor, 1980) which suggests that the increased social accessibility of higher density city life may have positive effects on the psyche. Finally, a hallmark theme of the classical theory was its anthropocentrism. Catton and Dunlap (1978), for example, note that Durkheim's insistence that social phenomena must be explained only by other social phenomena, and Weber's insistence that the methods and concepts of the social sciences must be kept separate from those of the biological sciences, has led to a deliberate omission of biophysical considerations and their relations to human society.

3.1.3 Urban Ecology

While the early sociologists focused mainly on the urban experience, urban ecologists began to question why cities took on a particular form. The principle concern of urban ecology is how people choose to spread out and arrange themselves within the urban environment (Paddison, 2001). Key early contributors, who were influenced by Tönnies, Simmel and Durkheim (Kleniewski, 2002), include *inter alia* Robert Park (1864 – 1944), Ernest Burgess (1886 – 1966) and Louis Wirth (1897 – 1952).

During the 1920s, Robert Park established the first urban studies centre in the sociology department at the University of Chicago. As the founding father of 'human ecology'[61], Park metaphorically applied biological processes and concepts to the social world (Kleniewski, 2002; Thorns, 2002; Orum and Chen, 2003; Bounds, 2004). His theory of urban ecology encapsulates forces similar to those of Darwinian evolution, such as competition (between classes and ethnic groups), dominance (by one group at the expense of others), succession (a dominant group taking over from a defeated group), and invasion (by a defeated group, initiating the process again), which were observed in the struggle for scarce urban resources, especially land (Saunders, 2001; Buttel and Humphrey, 2002). This led ultimately to the division of urban space into specific 'ecological niches' in which the occupants shared similar social characteristics through enduring the same 'ecological pressures' (Flanagan, 1993; Kleniewski, 2002). Park's greatest contribution was arguably his departure from purely theoretical study, and his insistence that it was crucial to 'get out there' and observe how urban environments actually worked (Kleniewski, 2002).

Ernest Burgess of the Chicago School suggested that urban settlements develop by growing outwards in a series of concentric rings over time (Flanagan, 1993; Kleniewski, 2002; Thorns, 2002; Orum and Chen, 2003; Bounds, 2004). Burgess's concentric zone model consisted of five main zones: central business district (CBD); circling the CBD, an area in transition containing business and light manufacture; residential area for industry workers who had moved from zones 1 and 2; residential area of higher class single family dwellings or apartments; and a commuter zone of suburban areas or satellite urban areas (Figure 3.1(a)). Although his model was inspired solely by his study of Chicago, he believed it to be representative of any urban settlement.

[61] Human ecology seeks to isolate the forces at work within an urban community which facilitate ordered groupings of people and institutions, and describe the typical clusters or constellations of persons and institutions brought about by the cooperation of these forces (Park, 1967[1916]).

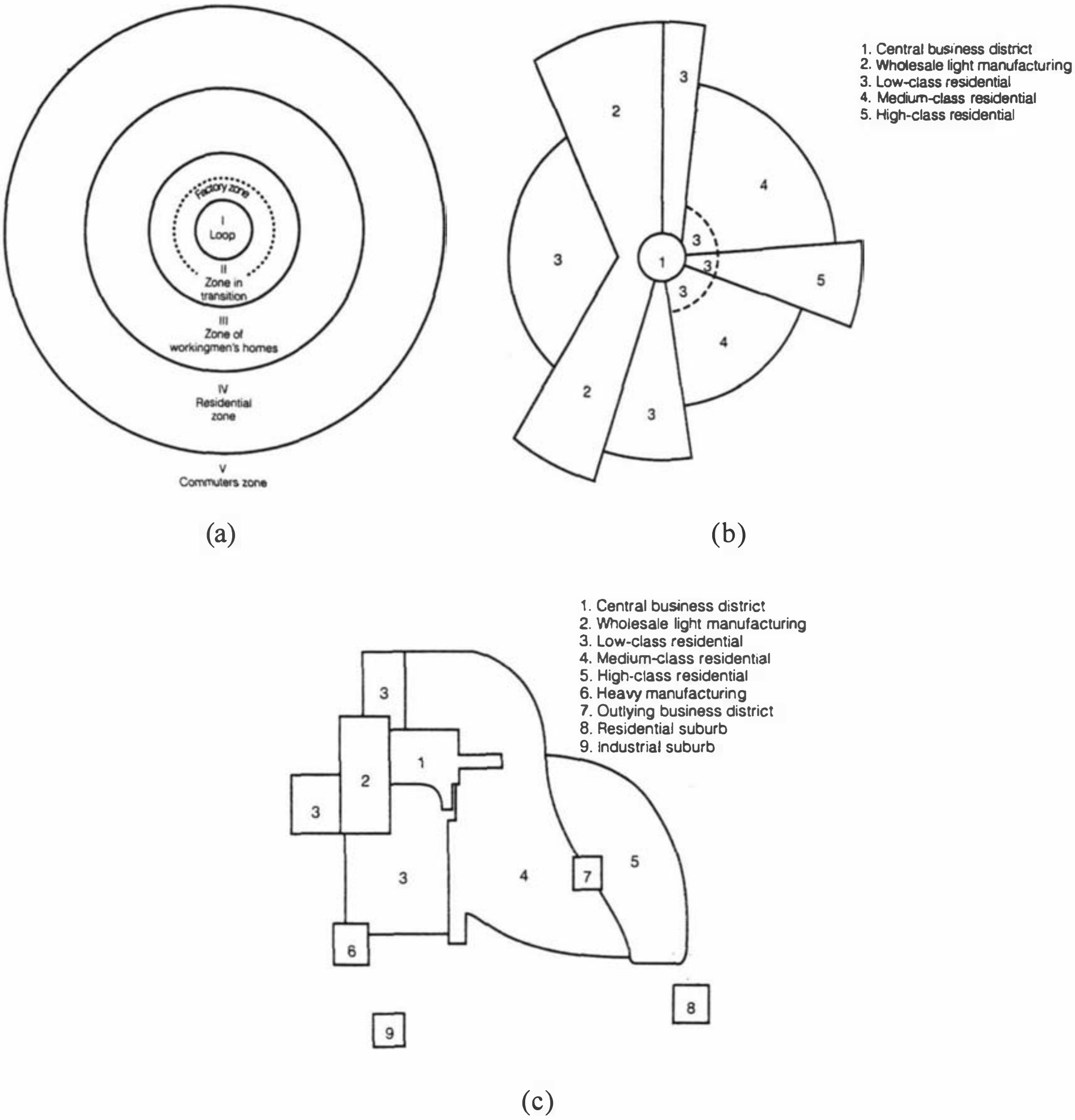

Figure 3.1 **Urban Ecology Models of Urban Development** (a) Burgess's Concentric Zones Model, (b) Hoyt's Sector Model, and (c) Harris and Ullman's Multiple Nuclei Model. Source: Kleniewski (2002, pp.31-33).

In 1938, Louis Wirth of the Chicago school combined theory with empirics in his essay *Urbanism as a Way of Life*, by synthesising the insights of previous urban sociologists, with an empirical focus on urban lifestyle. Wirth drew up a set of universal social characteristics of the urban environment, and analysed the effects of these on urban social life. He viewed the urban community as a large, dense, permanent settlement comprising socially and culturally heterogeneous individuals – a function of population size, density and heterogeneity (Macionis and Parrillo, 1998). Wirth saw the urban environment as an acid that over time dissolved traditional values and undermined the formation of meaningful relationships. In his view a humane urban environment could only be created through the intense efforts of urban planning.

While the early European sociologists produced much theory, the American urban ecologists conducted actual research, publishing many descriptive studies. Criticisms of the Chicago School have, however, called into question the applicability of Park's ecological theory and Burgess's concentric zone model. Firstly, apart from older U.S. cities, further examples of Burgess's model are not readily found (Bounds, 2004). Secondly, the appropriateness of using ecological concepts such as competition, succession and invasion to explain human behaviours has been hotly debated (Berry and Kasarda, 1977). Thirdly, Burgess's assumption that settlements are primarily based on transportation systems has been rejected. And, finally, the critical factor of choice through human intellect makes a comparison between ecology and the urban environment unsatisfactory. Despite these limitations, numerous alternative urban ecology models and theories have developed, taking into account more complex urban forms.

Other notable theories, which attempted to address the deficiencies of the early Chicago School theorists, include the sector theory (after Hoyt (1939)), the multiple nuclei theory (after Harris and Ullman (1945)), social area analysis (after Shevky and Williams (1949) and Shevky and Bell (1955)), and factorial ecology (after Pederson (1967) and Johnston (1976)). The sector and multiple nuclei theories are depicted respectively in Figures 3.1(b) and 3.1(c).

Hoyt (1939) made a block-by-block study of residential patterns in 142 cities between 1900 and 1936 to form his sector theory (Flanagan, 1993; Kleniewski, 2002; Thorns, 2002). His main findings were: upmarket areas formed different sized sectors; many sectors were pie-shaped rather than ring-shaped; poorer areas were frequently adjacent to, or surrounded, more upmarket areas; over time, sectors exhibited a tendency to move out of the city radially; and over time, popular areas could be found in two or three different places, being influenced by not only competition and population movement, but also other factors.[62] In 1945, Harris and Ullman extended Hoyt's residential study, arguing that urban growth is not predictable or inevitable, but diversifies into many distinct sectors of activity in the form of multiple nuclei (Kleniewski, 2002).

Shevky and Williams (1949) and Shevky and Bell (1955) followed a new direction by analysing urban land use in terms of the social characteristics of the inhabitants. They believed that variations among the three easily measured characteristics of economic status, namely, family type, income, and ethnicity formed the basis of the urban social structure, with the population of a particular sector sharing a high degree of similarity in these characteristics (Flanagan, 1993; Kleniewski, 2002). They termed these homogeneous sectors 'social areas'. Social area analysis

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[62] Hoyt observed, for example, that wealthier residents opt for neighbourhoods on higher ground, indicating that they see themselves as above poorer residents.

has, however, been strongly criticised as offering only limited descriptive insight into urban land use, but has no inherent predictive or explanatory value (Hawley and Duncan, 1957).

Factorial ecology employs computer techniques to analyse the social traits of an urban population. It differs from social area analysis in that it analyses clustered social traits that might influence urban form, rather than a few selected social traits (Flanagan, 1993; Thorns, 2002). Several characteristics may be grouped together into a single factor – socioeconomic status and family status, for example, have been used by researchers such as Pedersen (1967) and Johnston (1976) to explain specific residential land use patterns. Berry and Rees (1969) found that factorial ecology, rather than discrediting the concentric zone, sector and multiple nuclei theories, has shown that these approaches all exhibit a degree of partial correctness, but none captured the full complexity of urban land use due to its isolated focus on one or only a few social characteristics. Factorial ecology has thus shown that residential land use patterns are the combined influence of multiple factors.

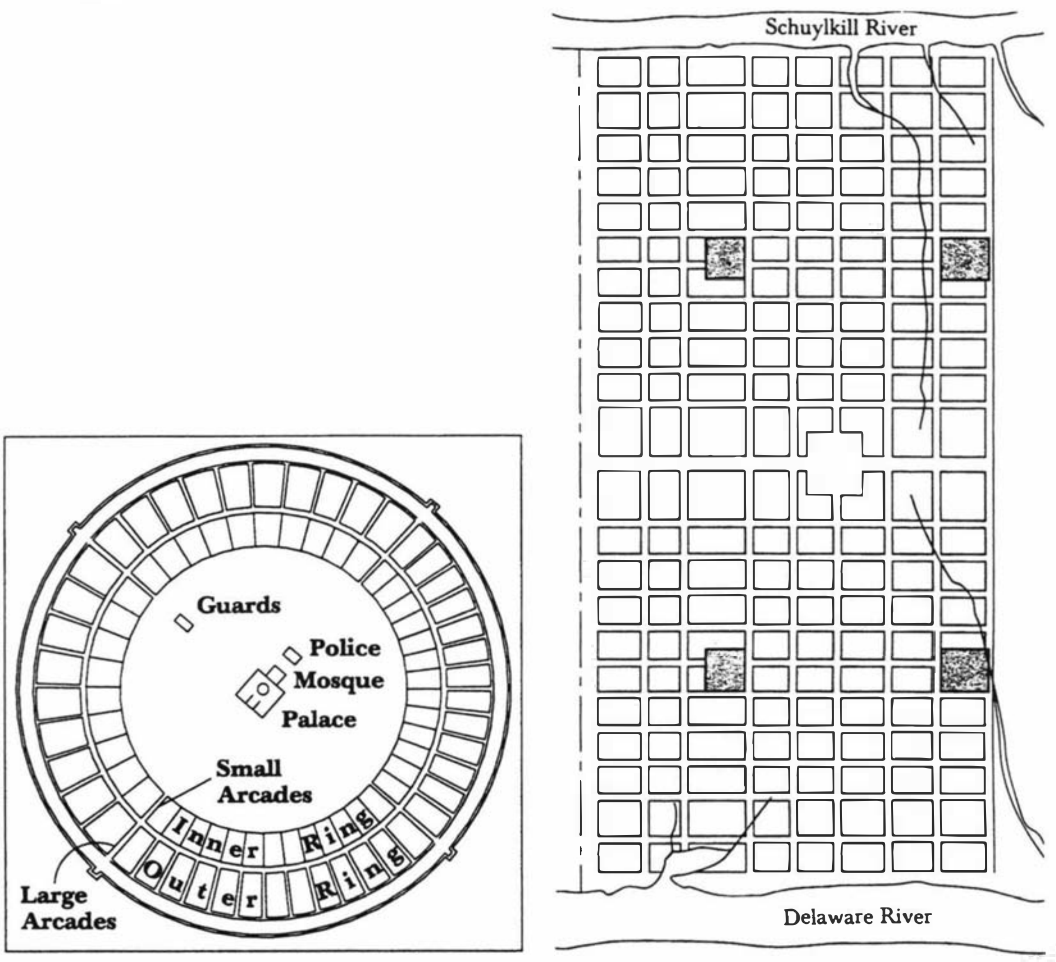
Factorial ecology, although remaining an accepted approach in explaining urban land use, has been criticised on several fronts. Firstly, the method relies on census tracts, which are not always socially defined districts and are known to contain coding and data errors. Secondly, the method has only been applied to a selected few cities around the world – further case studies are required to test its validity. Finally, many urban geographers and sociologists believe that urban land use patterns are also the result of capitalist market forces which are largely downplayed in factorial ecology.

3.1.4 Urban Geography

The focus of urban geography is on the significance of urban location, and in particular availability of natural resources and landscapes (Macionis and Parrillo, 1998; Pacione, 2001). An urban community has physical needs such as a hospitable environment, and access to adequate supplies of food, water and building materials. Furthermore, social reasons for a particular location may exist, namely: natural crossroads or 'break-of-bulk' points[63], access to valuable raw materials, amenity, administrative or political functions of government, strategic military capability, and religious or education reasons (Macionis and Parrillo, 1998). A combination of suitable environmental and social conditions will facilitate urban development, with an urban region's importance typically determined by the degree to which these physical requirements are met.

[63] These are locations where bulk goods are transferred from one type of transportation to another.

The form or physical shape taken by an emerging urban settlement reflects not only its physical environment, but also its social and economic functions. Figures 3.2(a) and 3.2(b) depict two patterns of a city's physical development, namely the radiocentric and gridiron city (Macionis and Parrillo, 1998; Pacione, 2001). Radiocentric cities, which radiate out from a common centre, originated in preindustrial times out of a need for protection. Other reasons for radiocentric formation are equal proximity to the city centre as the city grows, and the shortest possible access routes to the centre – these take the form of radiating lines, like spokes in a wheel. The radiocentric design is the exception in North America, where many downtown areas of well-known cities are gridiron-shaped. This form, composed of straight streets crossing at right angles to form city blocks, is typical of post-Industrial Revolution design. It facilitates economic activity, such as movement of people and products, and the subdivision of land for real estate.



(a) (b)

Figure 3.2 **Urban Geography Models of Urban Development** (a) The Radiocentric City: Baghdad circa 146-763 C.E., and (b) The Gridiron City: Philadelphia, 1682. Source: Macionis and Parrillo (1998, pp.168, 172).

Urban geographers provide three pathways for the physical expansion of cities: horizontally, vertically, and interstitially (toward a greater density) (Blumenfeld, 1949). The dominant pattern depends on available technology. Before motorised transport such as elevators, cars, buses or trains, and construction materials such as steel frames, growth was mainly interstitial with intensification of buildings taking up all available land. With the advent of buses and trains, the city spread out along transport lines and clustered in suburbs around transport nodes such as railway stations. Once the automobile was in use, the spaces between these nodes filled up, although still less densely settled than the city centre. Similarly, the advent of steel framing and the Otis elevator permitted the city to grow skywards at increasing densities.

Urban geographers have also paid attention to how urban settlements form in relation to one another. Settlements exist because selected activities can be performed more efficiently if they are clustered together rather than dispersed. Most towns develop a service function for their surrounding hinterland – such settlements have been termed ‘central places’ (Pacione, 2001). Urban geographers argue that the location of central places reflects the general population distribution i.e. an evenly spread population will result in an even spread of central places, while an unevenly spread population will result in central places being typically located where most accessible. Central places that serve large populations typically offer more specialised services and often grow progressively larger. A growth pattern emerges with various grades of central places distinguished by population size and zones of influence. This has become known as Central Place Theory.

One of the most commonly cited applications of Central Place Theory is the 1930s work undertaken by Christaller (1966/1933) in southern Germany and later reformulated by Losch (1954/1943). This fundamentally economic approach to analysing central places predicts how, through competition for space, an optimal pattern of settlement will emerge (Pacione, 2001). According to Christaller (1966/1933) each central place has a circular trade area – ideally this would be hexagonal for maximum efficiency. Settlements with the lowest levels of specialisation would be equally spaced and surrounded by hexagonal shaped hinterlands. For every six low specialisation settlements there would be a larger more specialised central place, say, township, which, in turn, would be equally distant from other townships, and so on (Figure 3.3). Christaller’s theory has been criticised on various grounds including its limited applicability, economic determinism, and static formulation.

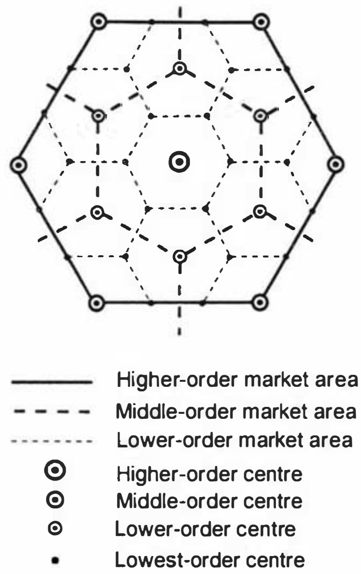


Figure 3.3 Hierarchical and Spatial Arrangement of Central Places. Source: Pacione (2001, p.118)

Diffusion theories provide an alternative to Central Place Theory by means of analysing the processes by which settlements spread from the point of initial colonisation (Pacione, 2001). The idea behind diffusion models proposed by *inter alia* Bylund (1960), Morrill (1963) and Hudson (1969) is that human behaviour, as applied to the formation and growth of settlements, occurs gradually over time and may be described as chaotic/random within certain limiting conditions. The elements of time and indeterminacy of behaviour are the central tenets of diffusion theory.

In his application of diffusion theory Morrill (1963) applied a historical-predictive approach based on Monte Carlo analysis[64] to describe the location of settlements. Hudson (1969) attempted to integrate diffusion theory with central place theory by drawing on the ecological principles of colonisation, dispersal and competition to illustrate the spatial pattern of settlements. Although diffusion theory possesses analytical explanatory power, the great variety of settlement forms and distributions has meant that more meaningful interpretations were required, particularly with reference to the influence of political and social forces operating at different spatial scales.

3.1.5 Urban Psychology

Human reactions to the physical and social urban environment represent an urban social psychology. Ordering urban environments through mechanisms such as mental mapping, developing social codes of behaviour and establishing urban networks, aids people in the

[64] A stochastic modelling technique in which behavioural choice is governed by a set of probabilities.

formation of a sense of urban Gemeinschaft. This provides people with emotional security, making urban society more meaningful and enjoyable.

In the 1960s and 1970s, Kevin Lynch became concerned with how people make sense of the urban environment. In *The Image of the City*, Lynch (1960) presents the concept of 'legibility', or mental mapping, of the urban environment. He discovered that people based their own mental image of the urban community on the five elements of paths, edges, districts, nodes and landmarks (Wirth-Nesher, 2001; Popenoe and Michelson, 2002). Lynch found that urban environments differed markedly in 'imageability', with strong imageability heightening the potential for an intense human experience of urban life. In a study of New Yorkers and Parisians, psychologist Stanley Milgram found that people's mental maps are based on personal experience, their interests, and their understanding of socially acknowledged important areas of the urban environment (Milgram, 1972; Duncan, 1977; Thill and Sui, 1993; Kulhavy and Stock, 1996). Milgram also found that this mental image keeps on changing, and that no one is able to recreate the complexity of the entire urban area. Urban environments are thus a dynamic, creative, continual mixture of experiences.

In Tönnies' Gesellschaft society, individuals coped with vast numbers of people and the accompanying anonymity by observing an intricate set of social rules. Social and psychological security in urban society rests on interpersonal relationships formed through urban networks. Studies by Suttles (1968), Howell (1973), Fischer *et al.* (1977) and Gans (1982) revealed that many Gemeinschaft relationships exist in an urban neighbourhood, with strong ties forged with family, neighbours and friends. Lofland (1973) proposed that, since not everyone has a traditional location such as a neighbourhood for developing interpersonal relationships, many people transform areas into private or semi-private space (Flanagan, 1993; Popenoe and Michelson, 2002). Irwin (1977) termed such places 'scenes' – typical scenes include bars, clubs, or urban areas taken over by a particular group.

3.1.6 Urban Political Economy

Toward the end of the 1960s, social scientists found that the theories of urban sociology, ecology, geography and psychology were inadequate in explaining contemporary developments in urban life. Walton (1981) asserts that the inadequacies/deficiencies of the early sociological theorists and of the urban ecology model in not only explaining prevailing social conditions, but in anticipating conflict and change, provided the impetus for the emergence in the early 1970s of a 'new urban sociology' or 'urban political economy'. This approach directs attention to how social conflict, inequality and change affect urban settlements globally (Gottdiener and Feagin, 1988; Flanagan, 1993; Gottdiener, 1994; Kleniewski, 2002).

Urban political economy argues that urban dynamics are heavily influenced by investment decisions and economic trends, in particular: urban settlements emerge within the larger political structures of county, state, nation and the rest of the world; local economies do not operate in isolation, but are linked together to form state, national and international economic networks; and political and economic institutions such as governments, international corporations and banks, and their investment decisions, are critical in shaping urban life. Under the influence of Marx, Engels and Weber (Kleniewski, 2002), authors such as Henri Lefebvre, David Harvey, Manuel Castells, Allen Scott, and Logan and Molotch drew heavily on political economic and Marxist theory in their attempt to understand urban form, in particular the social structures and processes of change that privilege some to the detriment of others.

Henri Lefebvre, a French philosopher, extended the ideas of Marx and Engels by applying socioeconomic concepts to an understanding of the unevenness of urban development (Macionis and Parrillo, 1998). Lefebvre suggested that urban development, particularly as manifested by differences in economic growth, was a product of the capitalist economic system. He identified three core influences: two circuits of capital (i.e. the primary circuit being investment capital for industry, and the second circuit real estate investment); space as a part of social organisation (i.e. the construction of space to meet needs is closely linked to behaviour); and the role of government in managing space (i.e. government influences land use patterns through urban development decisions such as roading, zoning, funding, taxes and so on). Lefebvre classified space as either abstract space – the environment envisaged by business, investors and government in terms of size, location and profit; or social space – the environment envisaged by the individuals who live, work and play there (Orum and Chen, 2003). These two perspectives result in a conflict along the lines of Marx's class conflict. Lefebvre's work is often considered a seminal contribution to the study of urban development.

David Harvey, a prominent English geographer in the 1970s, used Lefebvre's ideas on the second circuit of capital to illustrate how capitalist real estate investment directly shaped social inequality in Baltimore (Flanagan, 1993; Kleniewski, 2002; Orum and Chen, 2003; Bounds, 2004). Selective capitalist investment in the housing market, combined with government intervention serving capitalist interests, resulted in highly uneven urban development. In this way, Harvey illustrated the role of finance capital, rather than industrial capital, in determining a city's use of space (Figure 3.4).

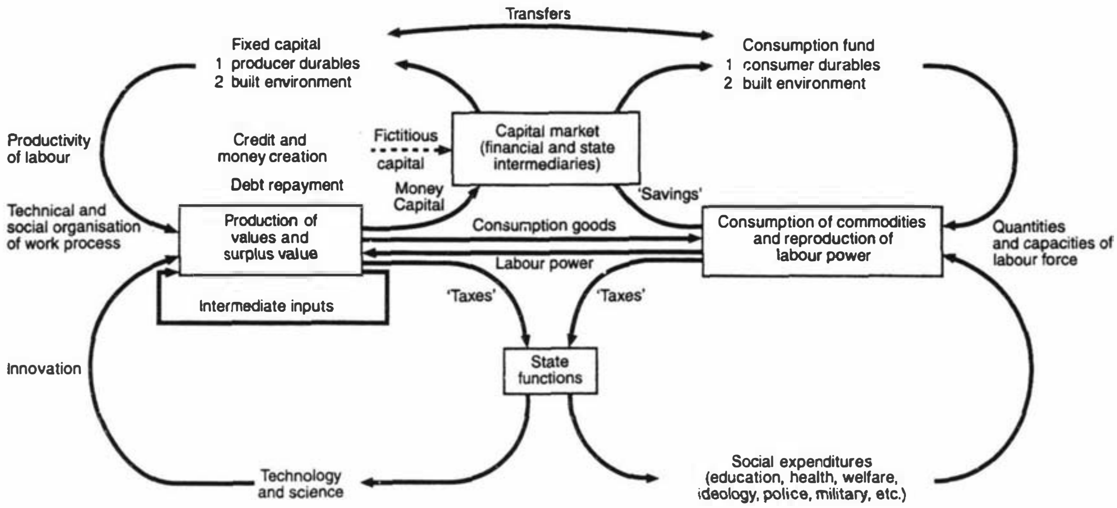


Figure 3.4 **Harvey's Model of the Circulation of Capital.** Source: Pacione (2001, p.143)

Manuel Castells highlighted the conflict between local government and the working class arising from local administration of various social welfare programmes. Castells viewed welfare capitalism as an effort by government to extend capitalism, resulting in new urban struggles and patterns of conflict affecting urban life. He also introduced the concept of 'mode of development'.[65] Castells suggested developing new forms and sources of information were a key element in today's informational mode of development (Orum and Chen, 2003; Bounds, 2004). Thus, corporate location no longer relied on proximity to sources of raw materials and labour, but was increasingly found in suburban or peripheral districts.

In the 1980s the English geographer Allen Scott studied the relationship between urban growth and economic globalisation. He analysed the impact of changes in the production process on urban space and suggested that urban growth patterns were determined by powerful transnational corporations (TNCs) rather than territorial competition as per the urban ecology model (Macionis and Parrillo, 1998). Two major contributions by Scott were the ideas of (1) horizontal integration – companies in the past were small entities that centralised all their functions in one location, but gradually, through absorption and consolidation of competitors, expanded their operations. Headquarters were maintained in a central location, but production plants and distribution centres were established in other more advantageous locations; (2) vertical disintegration – from the 1970s, companies began divesting themselves of their production companies, instead awarding contracts to suppliers through a process of competitive bidding. Many of the new production companies were located where labour and energy costs

[65] This was an adaptation of Marx's 'mode of production' concept. Marx saw the discovery and application of new sources of energy as a key element in the industrial mode of production.

were low, allowing large companies to conduct competitive business on a global scale, becoming multi- or transnational.

Logan and Molotch (1987) use political economic theory to identify central decision makers on urban growth in North America. They view urban development in terms of Lefebvre's categories of 'abstract space' and 'social space', with local conflicts arising between pro-growth and anti-growth factions (Boyle and Rogerson, 2001; Orum and Chen, 2003). They presented their theory of the 'growth machine', a coalition of entrepreneurs and urban politicians who favour increased economic development at the expense of smaller private sector entities, neighbourhood residents and other vulnerable stakeholders (Kleniewski, 2002; Orum and Chen, 2003). The growth machine's focus on the high profits that often accompany urban growth only extends quality of life to abstract space, failing to take into account the 'social space' ideas of local people.

The Global Economy: Cities as Consumers

A central tenet of the political economy approach is that urban change is linked to the development of a global economy. Regions of the world are increasingly being drawn into a single economic and political system (Wallerstein, 1979) which operates as a hierarchy, with countries at various stages of development constituting the 'core' (most economically developed), 'semi-periphery' (those with close ties to the core) or 'periphery' (the poorer less developed countries). The decision-making headquarters of TNCs, and their well-paid professionals, are typically situated in large cities in core countries. On the other hand, the manufacturing and distribution sectors, and their low-waged labourers, are located in the semi-periphery or periphery countries, where the impact of globalisation can be more negative than positive (Macionis and Parrillo, 1998; Orum and Chen, 2003).

Under globalisation, a 'post-industrial' city results; this is essentially a product of economic forces. Dramatic change has occurred as urban areas have moved away from manufacturing to become service centres, with a new focus on advertising, management, finance, and other business services as required to oversee investment activity in a global economy (Sassen, 1991; Kleniewski, 2002). Consequently, two labour markets have emerged: well-paid white collar professionals and low-paid service workers. Berry (1985, p.69) is pessimistic about this dichotomy, believing that the inequalities between the two will increase over time, resulting in cities with "islands of renewal in seas of decay".

A key consequence of the shift away from manufacturing to service provision is that globalised cities have become sites of consumption (Saunders, 1981; Orum and Chen, 2003; Miles and Miles, 2004). The role of consumption rather than production as a key influence on urban shape and form began to receive greater prominence in the later 1980s. Consumption in the urban context is both individual and collective. Individual consumption has significantly influenced a dispersed low density spatial structure, supporting development of a private transport-orientated, owner-occupied city. Collective consumption has also resulted in urban change, with a shift away from government provision of services such as healthcare, education, transport, and urban open space in favour of market provision of these services (Thorns, 2002).

Key Principles of the Urban Political Economy Perspective

Although urban political economists have emphasised different aspects of economic activity, general agreement exists on four foundational principles for analysing urban life: (1) urban development is not shaped by natural processes, but by human decisions made by those that control wealth and resources; (2) urban social arrangements reflect conflicts between rich and poor, powerful and powerless, and business and local communities over the distribution of resources; (3) government plays a key role in shaping urban life by allocating resources, mediating conflicts, and regulating economic activity; and (4) economic restructuring as a result of a global economy has significantly altered urban growth patterns (Macionis and Parrillo, 1998).

3.1.7 Brief Critique of the HEP-based Urban Schools of Thought

All the urban schools of thought so far reviewed assume no biophysical constraints to development of urban settlements. The inherently western idea of continued progress has helped to foster and reinforce the HEP assumption that all urban social and environmental problems can ultimately be solved through unlimited human ingenuity (Boyden *et al*., 1981). The early European sociologists, for example, focused on the city's potential for higher levels of rationality, specialisation and individuality by virtue of culture. Durkheim stressed that the causes of social phenomena should only be explained by social phenomena. Weber focused exclusively on historical and institutional considerations to the exclusion of the biophysical environment. Tönnies' Gemeinschaft-Gesellschaft typology similarly omits any consideration of ecological or biophysical constraints, despite the obvious shift in spatial configuration from one form of social organisation to another.

In urban psychology, the belief that the urban experience is very much subjective, that urban dwellers may reach higher levels of self-actualisation and sophistication, and that city life can be made more pleasant simply by cultural adaptation, reinforce the HEP assumption that cultural traits are more important than biological traits. Urban ecology, while appearing to acknowledge the biophysical environment, merely draws an analogy between ecological and urban environments, but fails to integrate these in any way. Similarly, the work on sector, multiple nuclei, and social area analysis, factorial ecology and urban geography utilised spatial units to explain urban form, but saw the spatial structure as primarily a manifestation of social processes (Michelson and Van Vliet, 2002). Urban political economy studies the influence of human political and economic systems in shaping urban environments, but makes little acknowledgement of the city's dependence on ecological resources, or the assimilative capacity of the environment to detoxify wastes, pollutants and emissions.

3.2 The New Ecological Paradigm

Evidence of serious environmental problems escalated throughout the 1970's and has since continued relentlessly in the form of major issues such as global warming, ozone depletion, acid rain, energy crises, and environmental disasters such as Bhopal 1984, Chernobyl 1986 and the Exxon Valdez 1989 (Dunlap, 1997, 2002). Environmental threats in the 1970s were problematic to adherents of the HEP, as they highlighted the interdependencies between the welfare of human societies and the biophysical environment. Sociologists such as Schnaiberg (1975), Anderson (1976) and Catton (1976a, 1976b) began analysing the causes of environmental degradation, and the impacts of pollution and resource scarcity on society. In doing so, they implicitly rejected the HEP assumption that human beings are exempt from ecological constraints (Dunlap, 2002). Catton and Dunlap (1978) argued this rejection supported the emergence of an alternative worldview which they termed the New Ecological Paradigm (NEP). Whereas the HEP represents the environment as something humans control for their own ends, the NEP presents the environment as critical for human life, as potentially fragile and limited in resources, and as imposing constraints on the achievement of unlimited human objectives (Catton and Dunlap, 1978; Dunlap, 1997, 2002; Dunlap *et al.*, 2002; Buttel *et al.*, 2002; Bell, 2004).[66]

[66] Note that the HEP/NEP dichotomy does not represent the poles of an anthropocentric-ecocentric continuum. Like the HEP, the NEP is inherently anthropocentric – it must be so to be considered a sociological paradigm, but it differs from the HEP by acknowledging humankind's critical dependence on the environment.

3.2.1 Assumptions of the New Ecological Paradigm

Catton and Dunlap (1978) and Dunlap (2002) outline four fundamental assumptions of the NEP, extracted from the writings of early environmental sociologists such as Burch (1971, 1976), Schnaiberg (1972, 1975), Anderson (1976), Catton (1976a, 1976b) and Morrison (1976). Firstly, despite their exceptional characteristics of culture, language and technology, humans are only one species among many that are interdependently involved in the global ecosystem. Secondly, human affairs are determined not only by social and cultural elements, but also by the complex cause, effect and feedback linkages in the web of nature, which produce unintended outcomes from purposive human actions. Thirdly, a finite globe means that physical and biological constraints restrict economic growth, social progress, and other human affairs. And finally, although human ingenuity may appear to extend carrying capacity, ecological laws (e.g. the laws of thermodynamics) cannot be revoked. The essence of the NEP is society's critical dependence on the biophysical environment (Dunlap, 1997, 2002).

The natural sciences, social sciences and humanities have typically studied human dependence on the environment in isolation of each other. According to Boyden *et al.* (1981), this excessive compartmentalisation, fragmentation and specialisation in human thinking has lies at the root of many social and environmental crises facing modern society. Clayton and Radcliffe (1997) argue that any strategy which attempts to instigate relatively unconnected changes to society, economy and environment is less likely to succeed compared with a systematic attempt to build integrated socio-economic and ecological systems. Understanding human activity and its implications requires an approach that focuses on the interrelationships between humans and their surrounding environment. A systems approach offers one such pathway for achieving this.

3.2.2 Cities as Ecosystems

In an article entitled "Cities are ecosystems!: new trend to study urban areas" in the journal *Ecological Economics*, Breslav *et al.* (2000, p.337) announced that "educators and scientists are joining forces to build a more comprehensive, interdisciplinary understanding of cities as ecological systems". This view is supported by Roseland (1992), Tjallingii (1993) and Newman (1999) who all believe the key to solving environmental problems is to view the city as an ecosystem[67,68], using inputs such as energy and materials (minerals, biomass, fossil fuels, land

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[67] The term ecosystem first appeared in a 1935 publication by British ecologist Arthur Tansley. It was however originally coined in 1930 by Roy Clapham, a colleague of Tansley's. Notable definitions of the concept have been made by Tansley (1935), Lindeman (1942), Evans (1956), Odum (1971a, 1983), King (1993) and Kay and Schneider (1994). Evans (1956), for example, defines an ecosystem as an organisational unit, comprising one or more living entities, through which energy and matter are

and so on), and producing outputs such as liveability (commodities, transportation, social networks and so on) and residuals (solid waste, water pollution, gaseous emissions and so on).

The view of the city as an ecosystem is most aptly summarised by Tjallingii (1993, p.7), "The city is [now] conceived as a dynamic and complex ecosystem. This is not a metaphor, but a concept of a real city. The social, economic and cultural systems cannot escape the rules of abiotic and biotic nature. Guidelines for action will have to be geared to these rules". Girardet (1992) proposes that an understanding of this urban biophysical functioning is crucial to sustainability. Newman (1999, p.220) asserts that the view of a city as an ecosystem is "one of the strongest themes running through the literature on urban sustainability". Baccini (1996), Nijkamp and Pepping (1998) and Decker *et al.* (2002) contend that the focus on sustainability is because cities are the major consumers of natural resources and producers of wastes. Implicitly, these justifications necessitate a transformation of the city from a less to a more sustainable form. Chapter 2 outlines the key principles for monitoring the progress of this transformation toward sustainability.

As an ecosystem, the city is a system, typified by resource inputs (e.g. land, water, fuels, foods, building materials and so on) and residual outputs (e.g. solid waste, pollution, emissions, toxins, waste heat and so on). Figure 3.5, for example, depicts Sydney's key resource inputs and residual outputs. To facilitate analysis of the city ecosystem, these fluxes are typically measured in material (i.e. mass) and energy terms. Furthermore, by considering the city as a whole, it is possible to conceive of management structures and technologies aimed at mimicking efficient natural processes, increasing eco-efficiency, recycling wastes, and reducing material and energy throughput. Girardet (1996, p.23) advocates a circular metabolism for cities where "every output can also be used as an input into the production system".[69]

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processed and transferred – a description that could arguably be applied to a city. Similarly, King (1993, p.24) defines an ecosystem as a system of "interacting biota and environment of some time-space domain". Odum (1983) provides further insight into where the ecosystem concept rests as an organisational unit by noting that the inclusion of the physical environment differentiates an ecosystem from a community.

[68] It is important not to confuse the treatment of the city as an ecosystem with the urban ecology school of thought. The former is typically concerned with a city's consumption of material and energy resources and production of waste outputs (Girardet, 1996; Newman *et al.*, 1996; Newman, 1999; Breslav *et al.*, 2000; Decker *et al.*, 2002). The latter simply uses the analogy of Darwinian processes of organisation within ecosystems to explain how people spread out and arrange themselves within the city (Flanagan, 1993; Macionis and Parrillo, 1998; Thorns, 2002; Orum and Chen, 2003), but fails to acknowledge any relationship between the city and the biophysical environment to which it is bound.

[69] Using the second law of thermodynamics Georgescu-Roegen (1971) has argued that complete recycling is physically impossible. Although others disagree with Georgescu-Roegen's (1971) assertion on theoretical grounds, they all agree that in practical terms complete recycling is impossible. Refer to Chapter 2 for further details on this topic.

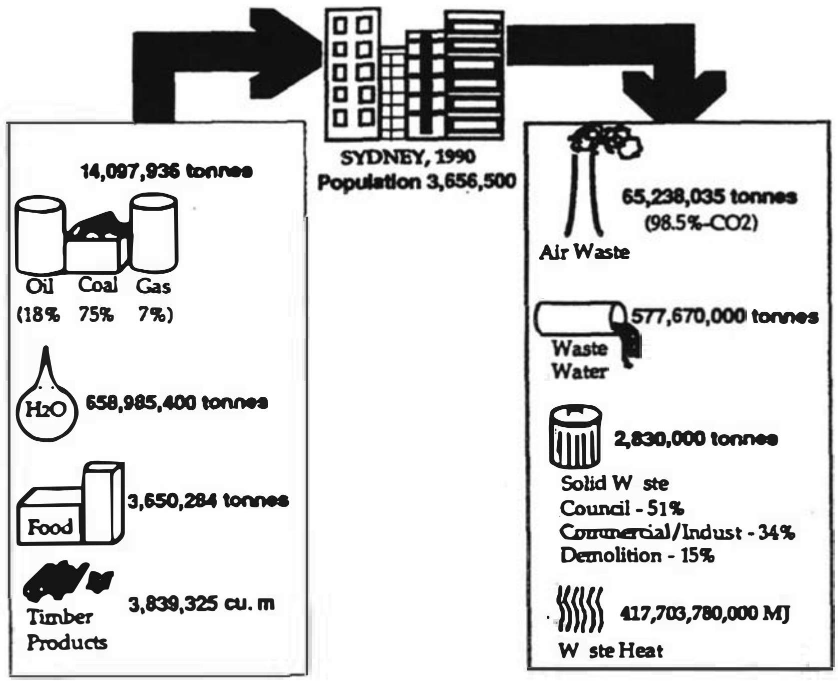

Figure 3.5 **Resource Inputs Consumed and Waste Outputs Discharged from Sydney, 1990.** Source: Newman (1996).

In studying the city as an ecosystem, several approaches have been pursued including urban metabolism and extended urban metabolism, energy analysis and emergy analysis. A brief discussion of these approaches follows (for further details refer to Wolman (1965), Newcombe (1975a, 1975b), Newcombe *et al.* (1978), and Boyden *et al.* (1981) – on urban metabolism; Newman *et al.* (1996), and Newman (1999) – on extended urban metabolism; Hannon (1973a, 1982), Bullard and Herendeen (1975a), and Brown and Herendeen (1996) – on urban energy analysis; and Huang (1998) – on urban emergy analysis).

Urban Metabolism

Furthering the 'city as an ecosystem' approach, the concept of urban metabolism views the city as an organism, utilising the metaphor of biological metabolism (i.e. the chemical process within an organism involving intake of resources, their transformation into more or less complex forms, and the subsequent excretion of wastes) to describe human processes (e.g. production and consumption) undertaken within cities. Urban metabolism provides a holistic framework for analysing a city's input-output relationships with its surrounding biophysical environment. Although urban metabolism studies are a relatively recent phenomenon (Girardet, 1992, 1996; Tjallingii, 1993; Newman *et al.*, 1996; Newman, 1999; PCE, 1998), their antecedents may be traced back much further.

Marx and Engels were the first to apply the term 'metabolism' to society to describe the material exchange between humans and nature in their critique of the capitalist mode of production (Fischer-Kowalski, 2002). Marx's use of the term was not however metaphorical, but referred specifically to plant nutrient cycles (Martinez-Alier, 1987). Spencer (1862) noted that societal progress is based on energy surplus, and that the amount of available energy explained differences in stages of advancement among societies. Nevertheless, it was not until Patrick Geddes (1854 –1932), arguably the founding father of town planning, that the key ideas underpinning urban metabolism were laid down (Martinez-Alier, 1987).

Geddes' (1885) thoughts on urbanism arose out of the birth and growth of vast urban areas in Great Britain – a transformation made largely possible through the burning of coal. The prevailing worldview of the time was a belief in unlimited industrial progress, but Geddes undertook an ecological critique of urbanisation, recognising that the availability of energy and materials imposed strict constraints on modern industrial activity. This included establishing an urban energetic and material budget in physical input-output terms – inspired by Quesnay's *Tableau Economique.* Geddes' table consisted of the sources of energy and materials transformed into products in three stages: extraction of fuels and raw materials; the manufacture, and transport and exchange. The table also included intermediary products used for manufacture or transport of the final products; calculation of energy losses between each of the three stages; and the resultant final product – which was often surprisingly small, in material terms, compared with its overall material inputs (Geddes, 1885; Martinez-Alier, 1987; Fischer-Kowalski, 2002). Through this analysis, Geddes proved to be ahead of his time as the first scientist to attempt an empirical description of urban metabolism on a macroeconomic scale (Fischer-Kowalski, 2002). Using the idea of society as a machine, he suggested the possibility of complete quantification of the way in which all matter and energy is integrated (and/or disintegrated) by transformation and by dissipation (Martinez-Alier, 1987).[70]

Unfortunately Geddes' ideas ran counter to the prevailing attitudes of his time and, thus, it was not until the mid 1960s that the concept of urban metabolism was revisited. Abel Wolman (1965) used urban metabolism in his study of a typical American city. He described the city in terms of the through-flow of energy and materials, and captured the salient features of the ecosystem approach, i.e. the city as a consumer of materials/energy and a producer of wastes. Wolman's work was not alone – seminal contributions were made by Newcombe (1975a, 1975b, 1976, 1977a, 1977b), Boyden (1977), Newcombe *et al.* (1978), and Boyden *et al.* (1981)

[70] Authors like Martinez-Alier (1987) and Fischer-Kowalski (2002) note that Geddes' urban metabolism, as based on flows of energy and materials, is far closer to the study of ecology than the misnamed 'urban ecology'. Martinez-Alier (1987) even suggests that the new environmental sociology of Catton and Dunlap (1978) and Humphrey and Buttel (1982) should adopt Geddes as a founding father.

in their studies of Hong Kong.[71] The complete and comprehensive nature of that latter work deserves further praise as the first attempt "to study and describe a human settlement in a comprehensive and integrative way, taking into account physio-chemical, biotic, societal and cultural components ... and considering the dynamic interrelationships between them ... as they relate to human health and wellbeing and to the life-supporting properties of the biosphere" (Boyden *et al.*, 1981, p.xv).

Extended Urban Metabolism

Alberti (1996), Newman *et al.* (1996), PCE (1998), Newman (1999), Newman and Kenworthy (1999) and Newton (2001) advocate an 'extended metabolism' model to study the city. Figure 3.6 depicts Newman and Kenworthy's conceptualisation of the extended metabolism model. This model specifies not only the physical and biological basis of the city, but also its human basis. The physical and biological processes convert resource inputs into products and finally waste outputs, in a manner analogous to biotic metabolic processes. Underlying these processes are physical laws of nature, such as the laws of thermodynamics, where anything entering the system must pass through and ultimately exit in some form. The amount of waste exiting the system is therefore dependent on the amount of inputs required. In this way, all inputs and outputs can be accounted for in a balance sheet format. In this extended urban metabolism model, the economic and social aspects of sustainability are integrated by the inclusion of liveability (i.e. the human need for social amenity, health and well-being). By acknowledging human dependence on the environment the extended metabolism model belongs clearly to the NEP.

[71] Warren-Rhodes and Koenig (2001) have since published an update of the Newcombe *inter alia* work on Hong Kong's urban metabolism.

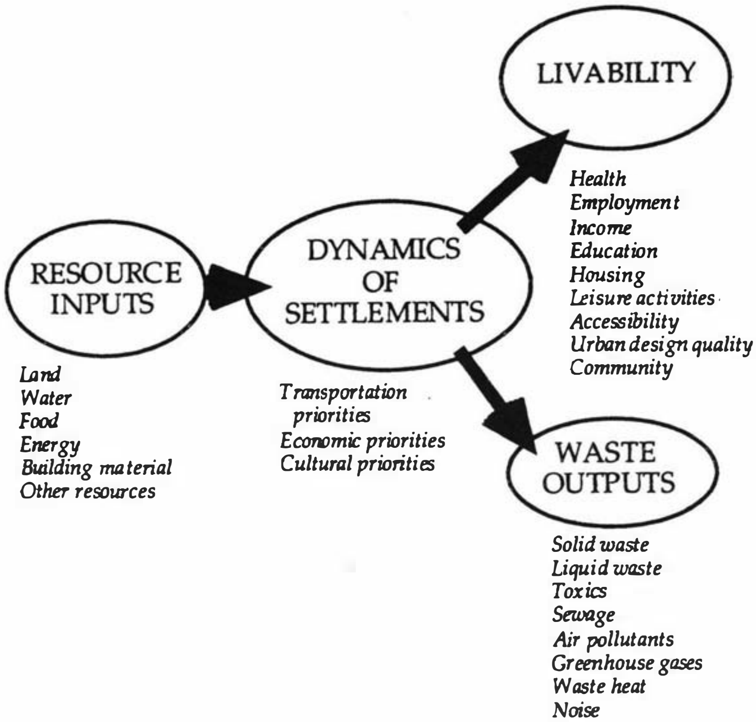

Figure 3.6 **Extended Metabolism Model of Human Settlements.** Source: Newman and Kenworthy (1999, p.8).

Energy Analysis of Urban Settlements

Energy analysis, a tool based upon thermodynamics, entails the determination of the energy required both directly and indirectly by a system (usually an economic system) in the process of producing a good or service (IFIAS, 1974; Hendtlass *et al.*, 1988). The motivation behind energy analysis is the quantification of the connection between human activities and the demand for energy (Brown and Herendeen, 1996). Energy analysis attempts to make explicit not only the direct use of energy in production, but also indirect (i.e. as appropriated through production chains) energy requirements. The realisation that energy is a scarce and essential resource for all production processes has been a key impetus behind the focus on energy (Chapman, 1977). Notable energy analysis studies at a national level have been carried out by *inter alia* Bullard and Hannon (1976) and Bullard *et al.* (1978) for the US economy, Denton (1975) for the Federal Republic of Germany and, in the New Zealand context, by *inter alia* Peet (1986), Hendtlass *et al.* (1988), Cocklin *et al.* (1989) and McDonald *et al.* (1999). Although there are fewer examples of energy analysis at the regional or urban level (Brown, 1981), studies include Odum and Brown (1975) and Browder *et al.* (1976) for the region of South Florida, Jansson and Zucchetto (1978) and Zucchetto and Jansson (1979) for Gotland, Sweden, and, in the New Zealand context, McDonald *et al.* (1999) for Auckland Region, Hamilton City and Whangarei City.

Emergy Analysis of Urban Settlements

Huang (1998), in a case study of Taipei, seeks to understand urban ecosystems, explaining the hierarchical spatial organisation of cities using methods of analysis based on Odum's (1986) concepts of emergy[72] (i.e. embodied solar energy) and transformity[73]. He argues that since transformity increases in a system with the number of energy transformations, and that in urban settlements energy transformations typically increase when moving from geographically dispersed to more centralised areas (i.e. energy flows from the surrounding landscapes to converge on urban centres), it therefore follows that an urban energy hierarchy must exist. For Taipei he identifies a hierarchy of five zones (ranked from highest to lowest): a mixed use urban core, a high density urban residential district, a service and manufacturing district, an agricultural district, and a natural area, each drawing resources from the next zone outward.[74] He noted that over time, zones of higher order develop successively as a result of energy convergence, with each zone evolving and being forced, in response to external changes, to adapt its internal structure. Urbanisation may therefore be seen as the process of change in the type of energy sources utilised. Moreover, this process of change will be reflected in the urban ecosystem's internal self-organisation.[75]

Limitations of the Urban Ecosystem Approach

Although the study of the city as an ecosystem is a useful tool for understanding of the functioning and sustainability of urban systems, the city ecosystem differs from natural or biological ecosystems in several important ways:

- *Ecological versus social variables.* Biological metabolic processes differ from those of the urban setting in that natural ecosystems do not exhibit the social variables which divide, mobilise and powerfully influence the actions of human beings[76] (AUICK, 1994). As such,

[72] Emergy is defined by Odum (1996, p.288) as "all the available energy that was used in the work of making a product and expressed in units of one type of energy".
[73] Huang (1998, p.501) defines transformity as "the ratio of energy of one type required to produce a unit of energy of another type".
[74] The spatial arrangement of these zones would appear to favour a concentric formation where zones with higher energy hierarchy are located in the centre, with energy hierarchy of zones decreasing outwards. However, rapid urban sprawl results in uneven overlap and encroachment of adjacent zones when, for example, patches of the natural zone are developed and converted to suburban residential districts (Huang, 1998).
[75] This represents an alternative to the earlier zonation theories of such as Burgess's Concentric Zone Model (Park *et al.*, 1925), Hoyt's (1939) Sector theory and Harris and Ullman's (1945) Multiple Nuclei theory.
[76] The extended metabolism model of *inter alia* Newman *et al.* (1996) attempts to address this by the inclusion of social aspects of sustainability into the model to achieve 'livability' in urban settlements.

the interlinkages between elements and flows within the urban ecosystem are not as tight as those within a biological ecosystem (Marcotullio and Boyle, 2003).

- *Proximity.* In biological ecosystems, metabolic efficiency and particularly recycling are made possible by the physical proximity of producers and decomposers, thus minimising energy losses in material transport. In an urban setting, however, recycling efficiencies are reduced by the physical separation of producers from consumers (linked through long-distance trade exchanges), and of consumers from recycling facilities (Gasson, 2002).
- *Open versus closed systems.* Biological ecosystems are energetically open but materially closed systems characterised by cyclical metabolisms. The balance between their metabolic demands and environmental regenerative and assimilative capacity is brought about through negative feedback processes, making them sustainable. Urban ecosystems, however, are both energetically and materially open systems. They are driven by positive feedback processes such as population and economic growth, causing an imbalance between their metabolic demands and the regenerative and assimilative capacity of the surrounding environment – a situation that is ecologically unsustainable in the long term (Hughes, 1974; Husar, 1994; Gasson, 2002).

Toolkit of Methods for Furthering the Urban Ecosystem Approach

An array of operational methods developed over the last two decades that may be used to help understand 'cities as ecosystems': (1) industrial ecology, (2) materials flow analysis, and (3) physical input-output analysis. Generally these methods seek to understand the biophysical functioning of systems through the lens of energy and mass transformation that takes place.

Industrial Ecology. Industrial ecology sees human economic activity as an integral part of the larger ecosystems that support it, especially in terms of resource supply and waste assimilation. Ecological concepts such as carrying capacity and ecological resilience are used to examine the extent to which human economic activity is undermining environmental services critical to humanity (Graedel, 1994; Lifset and Graedel, 2002). Graedel and Allenby (1995, cited in Allenby, 1999, p.40), encapsulated the essence of the field as follows:

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimise the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimised include resources, energy, and capital.

A core element of the field is the use of a systems perspective. Lifset and Graedel (2002) outline several different forms which reflect this systems orientation: (1) lifecycle perspective – this is reflected in the use of formal methods such as lifecycle assessment (LCA) where the impacts on the environment of products, processes and services from resource extraction through production, consumption and finally disposal, are taken into account; (2) materials and energy flow analysis, including physical input-output tables – this involves tracing the 'industrial metabolism', or flux of materials and energy through the various economic processes from extraction to disposal at various scales. Compliance with the First Law of Thermodynamics is a critical component of research in this area, involving the mathematics of budgets, cycles, stocks and flows[77]; (3) systems modelling – formal methods such as dynamic modelling reveal the complex interactions and feedbacks between system components driving the behaviour of the system under study; and (4) use of techniques and insights from multiple disciplines.

Materials Flow Analysis. Bringezu and Moriguchi (2002, p.79) define materials flow analysis (MFA) as "the analysis of the throughput of process chains comprising extraction of harvest, chemical transformation, manufacturing, consumption, recycling and disposal of materials". MFA is based on a system of accounting, where the inputs and outputs of these processes are quantified in physical units, usually mass. These inputs and outputs may be chemical substances (e.g. carbon or carbon dioxide) or natural or technical compounds (e.g. coal or wood). Material flow accounting is only one of several steps in MFA.

Different strategies for a sustainable industrial metabolism have been pursued, but an underlying concept common to all is that of the embeddedness of the industrial system and its societal interactions in the biophysical system. One of these strategies is detoxification of the industrial metabolism – mitigation of release of polluting substances to the environment. A second complimentary strategy is dematerialization of the industrial metabolism – a reduction in the throughput of the economy as a whole by increasing efficiency. Schmidt-Bleek (1994a, 1994b, 1994c) introduced the factor concept with MIPS Factor 10, and Weizsäcker *et al.* (1997) with Factor 4, which, in consideration of current resource use by industrial economies, proposed a four to ten fold increase in resource efficiency. This eco-efficiency concept is not only concerned with inputs such as materials, energy, water and land, but also outputs to the environment such as pollutant emissions and waste, relating them to the products or services

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[77] Ayres *et al.* (1994) and Socolow (1994) cite applications in the study of toxic chemicals, resource depletion, environmental degradation resulting from residual wastes, and the perturbation of biogeochemical life-supporting cycles.

produced (OECD, 1998; EEA, 1999; Verfaillie and Bidwell, 2000; Bringezu and Moriguchi, 2002).

Physical Input-Output Analysis. A physical input-output table (PIOT) is a comprehensive and detailed physical accounting system based on macroeconomic activity (Strassert, 2002).[78] A PIOT traces not only the commodity flows of the traditional input-output table in physical units, but also the material flows across the environment-economy interface. While MFA is typically focused on economy-wide fluxes of mass and energy, PIOTs are structurally detailed, recording mass and energy exchanges across numerous industries. In this way complete materials balance can be achieved for the various economic activities (Stahmer *et al.*, 1997). A key feature of physical input-output analysis is that all repercussionary effects across by industry within an economy may be evaluated. The PIOT is conceptually consistent with the ideas of authors such as Boulding (1966) and Daly (1991) who view the economic production system as an open subsystem of the finite and non-growing natural environment. This economic subsystem imports low entropy matter-energy in the form of raw materials and exports high entropy matter energy, or waste (Daly, 1991; Strassert, 2002). This one-way flow, beginning with resources and ending with wastes, is analogous to a digestive tract in an open biosystem, connected to the environment at each end (Daly, 1995). Through incorporation of materials balance, the PIOT overcomes the major shortcoming of conventional national accounting, namely that the economic process is viewed as a closed circular flow from firms to households and back to firms, with no inlets or outlets (Daly, 1995; Strassert, 2002).

3.2.3 Ecological Footprinting

Wackernagel and Rees (1996) pioneered the concept of Ecological Footprinting. The Ecological Footprint (EF) is the area of land required to produce the resources consumed and assimilate the wastes produced by a given population (Rees, 2000). The EF is a sustainability indicator for two main reasons: (1) it measures the total ecological cost of supplying goods and services for a population both directly (actual land for agriculture, housing and so on), and indirectly (embodied land in products consumed); and (2) it invokes the ecological concept of carrying capacity (the maximum population that can be supported indefinitely by a given land area). Where a region's population 'overshoots' its carrying capacity, it is said to be in

[78] Geddes (1885) was ahead of his time in his attempt to develop a unified calculus based on energy and material flows, capable of providing a coherent framework for all economic and social activity. He developed a type of economic input-output table in physical terms, with the first column containing sources of energy and materials transformed into products. His work represents an embryonic form of an empirical description of societal metabolism on a macroeconomic scale (Martinez-Alier, 1987; Fischer-Kowalski, 2002).

'ecological deficit', using more productive land than it has available within its borders. This population can be said to be appropriating carrying capacity from elsewhere (Vitousek *et al.*, 1986; Wackernagel, 1991; Rees, 1992).

Ecological Footprinting highlights the fact that far from being geographically discrete, most of the land occupied or appropriated by urban areas lies beyond metropolitan boundaries (Rees, 1992). In this way, Ecological Footprinting reconnects the urban centre, as a focus of consumption, with its hinterland, a focus of production, through trade and natural flows of ecological goods and services. In an ecological sense, the city as a node of consumption can be seen as a parasite existing on a vast external resource base, not only importing carrying capacity, but also exporting ecological degradation through environmental and economic exploitation of distant locations. The effect of urbanisation and trade is thus to physically and psychologically distance urban populations from the ecosystems that sustain them (Rees, 1992). The interdependencies which are created between the urban region and distant locations may not be ecologically sustainable in the long term. Bicknell *et al.* (1998) and Ferng (2001), among others, have promoted input-output analysis as a systematic and standardised method for calculating EFs. McDonald and Patterson (2003c, 2004) have employed this approach to highlight the importance of ecological interdependencies at a regional level in New Zealand, stressing in particular what matters is not so much the size of the EF, but the location from which it is appropriated.

Numerous studies using Ecological Footprinting in an urban context have been carried out. Wackernagel and Rees (1996) found in a study on Vancouver, Canada, that the Vancouver Regional District of 1.6 million inhabitants and a land area of 293,000 ha, has an EF of 6,720,000 ha (or 23 times its geographic area). This equates to a per capita EF of 4.2 ha. Other researchers have reached similar findings. In a study of 29 cities in the Baltic Sea drainage basin, Folke *et al.* (1994) found that urban consumption of wood, paper, fibre and food was sustained by an ecosystem area 200 times larger than the urban area itself. EF studies of Canberra, Australia (Close and Foran, 1998; Lenzen, 2004) have revealed a 1998-99 EF of 1,790,575 ha which, with a population of 312,300, equates to about 5.7 ha per capita. Regional EF studies have been carried out in New Zealand at the national level by Bicknell *et al.* (1998), and at the regional/urban level by McDonald and Patterson (2002b, 2003c, 2004), including a number of urban areas. Auckland Region, for example, was found to have a 1997-98 per capita EF of 5.68 ha (adjusted for international comparison). These urban per capita footprints can be placed in context when it is considered that Wackernagel *et al.* (1999) estimate the average 'earthshare'[79] (considered the maximum sustainable EF allowance) to be 1.9 ha per capita.

Limitations of the Ecological Footprinting Approach

While the EF provides a valuable heuristic and pedagogic tool that captures current human resource use in a way that is readily understood (Costanza, 2000; Moffatt, 2000), the methodology does have several weaknesses and limitations, as discussed below:

- *A lack of common definitions and methodologies* for calculating the EF. A paucity of international conventions has led to ambiguities in interpreting the results of various EF studies.
- *Land as the numeraire.* Since land is not the only scarce natural resource, it is valid to question the use of 'embodied land' as the sole numeraire for the calculation of a sustainability indicator. Many have argued (Slesser, 1973; Gilliland, 1975; Costanza, 1980; H.T Odum, 1983; Herendeen, 1998) that a more appropriate numeraire might be 'embodied energy' or 'embodied solar energy'.
- *Hypothetical energy land* required for sequestration of CO_2 emissions often constitutes a disproportionately large part of the EF. Other emissions and pollutants have ecological consequences yet they are ignored. Critics have also questioned the use of afforestation as the preferred option for CO_2 sequestering.
- *Commensuration of different land types.* The use of 'equivalence factors' (adjustments made to take into account variations in biological productivities) is contentious. The focus on biological productivity ignores other relevant factors such as cultural values, social preferences or relative scarcity.
- *Dynamics – future scenarios?* EFs provide a snapshot of current population requirements, but fail to inform of likely future scenarios. EFs are thus always 'yesterday's news'. Key dynamic components of the sustainability equation such as intergenerational equity, technological change, and adaptability of social systems are overlooked, as are non-linearities, feedback loops, and thresholds (Holling, 1973; Levin, 1998) which are characteristic of complex adaptive systems.
- *Policy relevance.* The claim that EFs can evaluate potential strategies for avoiding ecological overshoot (Wackernagel and Rees, 1996; Wackernagel and Silverstein, 2000) is highly contested (Ayres, 2000; Moffatt, 2000). While the EF may not be sufficient for targeted policy action, it does however provide a high level indicator of

[79] 'Earthshare' is estimated by dividing the total amount of global productive land by the global population (Wackernagel *et al.*, 1999).

ecological impact. Its key feature is its ability to stimulate public awareness of the far-reaching ecological effects of human activities.

3.3 Outstanding Theoretical Issues

3.3.1 Need for Maturation of the NEP-based Approaches to Urban Sustainability

Urban theory has a long and rich history in the social sciences, spanning sociology, geography, psychology, and political science. While urban sociologists were concerned with the urban experience, fearing a breakdown of community ties and a subsequent negative effect on the human psyche, urban ecologists and geographers were more interested in how and where urban settlements arose and the factors that influence their internal arrangement. Urban psychologists focused on human reactions in adapting to an urban lifestyle, while urban political economists turned to social conflict, inequality and the greater political structures and processes of change in their search for an explanation of urban dynamics. The common thread in all of these schools of thought is their focus on the human condition with little or no regard for ecological issues. In spite of the increased environmental awareness of the last 20 to 30 years in academia, it is not surprising that most students of urban planning and studies are taught from an anthropocentric worldview that has dominated the social sciences over the last two centuries. Consequently, city and town planning practitioners and academics mostly operate within the HEP that underpins these disciplines.

On the other hand, NEP theoretical approaches to urban development are comparatively new and underdeveloped, while the NEP literature on urban issues is relatively thin and dominated by only a few authors.[80] Urban issues still seem to be largely the domain of the social sciences, rather than the natural sciences, in spite of the early bridging work of the father of town planning Patrick Geddes. The uptake of the NEP is more evident in non-urban areas of public policy such as catchment management, natural resource management and environmental conservation. Consequently, there is a clear a need to build and mature the NEP approaches to urban sustainability beyond the current urban ecosystem/metabolism and ecological footprinting approaches outlined in this Chapter.

This process of building and maturation could involve:

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[80] Only very recently, for example, was the journal of Urban Ecosystems established (March 1997).

- *Empirical studies.* A growth of empirical studies focusing on the ecosystem processes of cities and their ecological footprints. To date, there are few substantive studies (e.g. urban metabolism of Hong Kong) with most being of a more general nature. Without detailed and comparative empirical studies, the basis for developing theory and methods based on the NEP view of urban sustainability remains weak;
- *New ecological ideas and terms.* Development of specific ecological ideas uniquely applicable to cities and urban spaces. There is a tendency to draw ideas and analogies directly from biological ecology and apply them to cities. At the very least, we should be careful when applying ideas such as carrying capacity to urban situations;
- *Stronger links between HEP and NEP research.* Forging stronger links between the established HEP research and the more recent NEP thinking. For example, there are very few studies such as Huang (1998) that attempt to explain the ecological determinants of urban phenomena (e.g. spatial zonation) that has long been observed in the HEP literature. The two schools of thought most often operate in complete isolation of each other; and
- *Institutionalisation.* Institutionalising the NEP view of urban sustainability and building a critical mass of research activity in this area. Institutionally the NEP-based field of urban sustainability is weak with no strong international community of scholars or teaching institutions in this field. HEP scholars from the social sciences dominate the field, while NEP scholars in urban areas are often marginalised.

3.3.2 Need to Integrate the HEP and NEP Approaches?

The HEP and NEP approaches to urban sustainability and development have so far been presented in this thesis as dichotomous choices in that they are based on fundamentally different views of the world. HEP is based on the view that humans are unique among all species in that they have the 'know-how' to overcome any environmental problems, while NEP is based on the view that humans, like all species, are essentially constrained by ecological limits. Given these significantly opposing views, is it therefore feasible and/or desirable to attempt to integrate these two approaches?

One response to this question is that the HEP theories that focus on human behaviour, institutions and political economy are not so much wrong as incomplete. They simply fail to take account of biophysical constraints, thresholds and discontinuities. If, however, they could acknowledge biophysical limitations, the resulting theory would be all the more rich. The understanding in political economy theory, for example, of cities as nodes of consumerism and globalisation is insightful, but could be further enhanced by integration with the ecological footprint concept that links these consumerism/globalisation processes to their ecological consequences. Such integrational theorising could lead to some useful outcomes, with both the HEP and NEP perspectives being enriched. At some point, however, conflict between the assumptions that drive each paradigm might conceivably impose limits on such integration, e.g. the two perspectives are unlikely to accept similar assumptions regarding the ability of humans to overcome biophysical limits through technological advancement or environmental manipulation.

A second response therefore is to accept that integration of the HEP and NEP is mostly not feasible because the two perspectives have fundamentally different views of the world. In this case, 'methodological pluralism', rather than 'methodological integration', would appear to be the best way forward (Norgaard, 1989). In other words, both the HEP and NEP approaches can be pursued independently but in open dialogue with each other. The NEP scholars could continue to use ecological principles and ideas to explore issues of urban sustainability, which may provide useful insights into the public debate on urban policy issues as well as challenge HEP-based perceptions of urban development. Similarly, the HEP scholars would similarly explore issues of urban sustainability, but from their perspective. Dialogue and debate would ensue, and city planning practitioners would draw as appropriately from both the HEP and NEP streams when formulating plans and policies.

The approach taken in this thesis is to focus on the NEP-based concepts relating to urban sustainability, emphasising those ecological and thermodynamic sustainability principles outlined in Chapter 2. Rather than operating entirely in the ecological realm, however, an attempt will be made to link ecological factors with economic factors and, to a lesser extent, social factors.

3.4 Summary

A summary of the HEP and NEP worldviews and their different schools of thought is presented in Tables 3.1(a) and (b) respectively. The dominant anthropocentrism of the HEP contrasts clearly with the consideration of environmental constraints under the NEP, particularly in their different views of the nature of urban problems, and their proposed solutions to these problems. Furthermore, the compartmentalised approach of the HEP to urban settlements contrasts with the more holistic systems approach of the NEP.

It is important to note that energy and emergy analysis differ substantially (centre column of Table 3.1(b)), particularly in respect of conceptual underpinnings and accounting procedures

(Brown and Herendeen, 1996). Energy analysis involves determining the direct and indirect (embodied) energy requirements needed to produce a good or service (IFIAS, 1974). A key component of this analysis is calculation of indirect effects using an economic technique with strong similarities to that of input-output analysis (Bullard and Herendeen, 1975b). Emergy analysis uses principles of energetics (Lotka, 1922, 1925, 1945), system theory (von Bertalanffy, 1968) and systems ecology (H.T. Odum, 1975, 1983, 1988, 1991), to determine the value of resources, goods and services in terms of the solar energy it took to make them (called solar 'emergy'). While emergy analysis has pioneered the concept of 'energy form' (all energies are not of the same quality and are thus expressed in the equivalent solar energy units), energy analysis does not recognise differences in energy quality. For a more complete comparative view between embodied energy analysis and emergy analysis, refer to Brown and Herendeen (1996).

Table 3.1(a) Conceptual Foundations for HEP-based Urban Schools of Thought

	Human Exemptionalism Paradigm				
	Classical Urban Sociology c.1850-1920[1]	Urban Ecology c.1920-1975	Urban Geography c.1940-1980	Urban Psychology c.1960-1980	Urban Political Economy c.1975-
Scope of Area of Study / Themes	· Social order, cohesion & community ties · Social, economic & political power relations	· Arrangement of people within urban environment · Analogies drawn from ecology: competition, dominance, succession & invasion	· Significance of urban location & physical shape	· Human reactions to urbanisation · How people make sense of the urban environment	· Political structures · Investment decisions · Economic trends · Trade patterns · Globalisation
Relationships	social / economic	social	social	social	socio-political / economic
Examples of Contributing Authors	Marx, Engels, Tonnies, Durkheim, Simmel, Weber	Park and Burgess (1967), Wirth (1938), Hoyt (1939), Harris and Ullman (1945), Shevky and Bell (1955), Pederson (1967)	Blumenfeld (1949), Losch (1954), Christaller (1966), Byland (1960), Morrill (1963), Hudson (1969)	Lynch (1960), Suttles (1968), Milgram (1972), Lofland (1973), Irwin (1977), Gans (1982)	Walton (1981), Lefebvre (1991), Harvey (1978, 1985), Castells (1977), Logan and Molotch (1987)
Dominant Methodological Approach[2]	Structuralism (Marx, Engels, Weber); Environmentalism (Tönnies, Durkheim, Simmel)	Mainly Positivism, earlier work Environmentalism	Positivism	Behaviouralism and Positivism, more recently Humanism	Structuralism, to a lesser extent Managerialism & Postmodernism
Nature of Urban Problems	· Breakdown of community ties & relationships · Feelings of alienation · Exploitation of proletariat by capitalist bourgeoisie	· Dominance of particular groups at the expense of others · Traditional community values undermined · Meaningful social relationships difficult	· Unplanned urban growth patterns e.g. sprawl · Exhaustion or contamination of the resource which had initially led to the city's development	· Loneliness · Urban malaise · Alienation · Lack of community	· Institutional · Social conflict · Inequality · Uneven spatial development
Solutions to Urban Problems	· Overthrow of capitalism through revolution	· Urban planning	· Urban planning	· Social codes of behaviour · Urban networks · Establishment of Gemeinschaft-like relationships	· Policy change · Political mobilisation · Redirection of investment
Drivers of Urban Change	· Capitalism · Social, economic & political power relations	· Competition between classes / social groups · Technology e.g. transport, elevators, construction materials · Clustering of social factors e.g socio-economic status, ethnicity	· Technology e.g. transport, elevators, construction materials · Trade	· Planning for livability · Desire for heightened urban experience	· Global economy e.g. more open trade, TNC's · Investment decisions · Political structures · Governmental policy
Determinants of Spatial Differentiation	· Class structure · Complex division of labour	· Class structure · Technology e.g. transport, elevators, construction materials · Other social factors e.g. socio-economic status, ethnicity · Urban planning	· Technology e.g. transport, elevators, construction materials · Trade · Urban planning	· Urban networks & relationships	· Uneven investment · Real estate investment · Informational mode of investment · Employment opportunities
Future Prognosis for Cities / Limits to Cities	· Pessimistic - disintegration of social life & relationships · Urban malaise	· Pessimistic - if planning was unable to mitigate potential problems	· City needs to make the most of its strategic location to its advantage · Spatial / biophysical constraints govern physical growth and shape	· More meaningful experience of urban life through adaptive mechanisms · Urban life becomes a dynamic creative mixture of experiences	· Increased inequity · Sites of consumption rather than production · Growth opportunities as result of integration into global network
Potential Pros of Cities	· Self-actualisation · Individuality · Rationality	· Efficient organisation of urban space into 'ecological niches'	· Nexus of activity benefiting both the city and its surrounding hinterland · Economies of scale	· Higher levels of self-actualisation & sophistication	· Greater opportunities through integration of material & information flows across the globle · Economies of scale
Potential Cons of Cities	· Loss of sense of community · Alienation	· Conflict between social groups · Societal segmentation as a result of shared 'ecological' pressures	· Uncontrolled growth e.g. sprawl	· Failure to adapt may result in loneliness & isolation	· Marginalisation & alienation of those disadvantaged by globalisation

Note:
1. This Table considers only contributions made during the indicated periods.
2. Refer to Pacione (2001, pp.27-32) for definitions of these methodological approaches.

Table 3.1(b) Conceptual Foundations for NEP-based Urban Schools of Thought

	New Ecological Paradigm		
	Ecosystems View of Urban Settlements		Ecological Footprinting c.1990-
	Urban Metabolism & Extended Urban Metabolism c.1965-	Energy/Emergy Analysis c.1970-	
Scope of Area of Study / Themes	· Metabolism metaphor used to describe city as an organism	· Determination of energy requirements for urban functioning · Urbanisation seen as process of change in type of energy sources	· Evaluates land-based carrying capacity of a given population
Relationships	ecological / economic	ecological / economic	ecological / economic
Examples of Contributing Authors	Wolman (1965), Newcombe (1975a, 1975b), Newcombe *et al*. (1978), Boyden *et al*. (1981), Newman *et al*. (1996), Newton (2001)	Hannon (1973), Bullard and Herendeen (1975), Brown (1981), Peet (1986), Hendtlass *et al*. (1988), Odum (1996), Huang (1998)	Rees (1992), Wackernagel and Rees (1996), Bicknell *et al*. (1998), Ferng (2001), McDonald and Patterson (2003b, 2004)
Methodological Approach	Systems Theory; Empirical (energy and materials flow analysis)	Systems Theory; Empirical (energy accounting); Thermodynamics	Systems Theory; Empirical (embodied land analysis)
Nature of Urban Problems	· Cities encountering thermodynamic & biophysical limits · Linear metabolism	· Thermodynamic limits to energy availability · Convergence of energy flows on urban centres · Urban sprawl & degradation of surrounding natural landscapes	· Humans exceeding carrying capacity · Critical dependence on surrounding hinterland and other nations
Solutions to Urban Problems	· Circular metabolism · Mimicking of efficient natural processes · Reduction of material & energy throughput · Increased eco-efficiency	· Optimum efficiency for maximum power (emergy analysis) · Autocatalytic feedbacks to reinforce production (emergy analysis) · Maximise the flow of useful energy	· Appropriation of resources from localities with sustainable land management practices · Reduced and more selective consumption · Movement toward being self-sustaining
Drivers of Urban Change	· Industry growth · Material affluence · Recycling and energy policies · Waste management practices	· Thermodynamics · Maximum Power Principle (for emergy analysis) · Autocatalytic feedbacks (for emergy analysis)	· Consumption & production patterns · Interregional and international trade · Population growth
Determinants of Spatial Differentiation	· Relationship with rural hinterland · Natural resource and energy availability	· Energy availability · Zones with higher energy requirements tend to encroach on those with lower energy requirements	· Relationship with surrounding hinterland and other nations · Access to natural resources
Future Prognosis for Cities / Limits to Cities	· Urban growth outstrips material and energy resource base · Urban growth produces unsustainable levels of wastes · Urban growth is unsustainable unless 'dematerialisation' policies are adopted	· Slowdown of economic and societal progress in urban centres due to thermodynamic limits · Decline of cities and urban activities that are energy intensive	· Large urban ecological footprints are unsustainable, as long as there is an overshoot of international/national carrying capacities · Decline of cities over rural activities
Potential Pros of Cities	· Efficient use of natural resources due to economies of scale and spatial concentration of activities in urban areas	· Financial and control activities are appropriately located in urban centres, as this makes sense from an emergy hierarchy view	· Cities have low ecological footprints per capita cf rural footprints
Potential Cons of Cities	· Resource scarcity · Environmental degradation through waste, pollution, emissions · High infrastructural/technology costs to cleanse natural environment	· Uncontrolled encroachment of lower energy zones by higher energy zones · Ecological degradation · Reduced flows of useful energy	· Overshoot of carrying capacity is inevitable with all cities

Part II Environment-Economy Interactions in Auckland Region

A Static Systems Analysis

Chapter Four

Methodological Framework for a Static Systems Model of the Auckland Region

In this Chapter a *static systems* modelling framework of the Auckland Region economy, and how it interacts with its biophysical environment, is outlined in detail. This static systems framework is based on two extensions of conventional input-output analysis. Firstly, the analysis is extended to take account of the use of natural resource and ecosystem service inputs into the economy and the production of residuals (wastes) by the economy. Secondly, a physical input-output accounting system of the Auckland Region economy and its interaction with the biophysical economy is put forward, as a complementary framework to the conventional financial accounting framework used in input-output analysis. This physical input-output framework is important as it directly assists the understanding of the biophysical sustainability of the Auckland Region economy.

This methodological framework outlined in this Chapter is then operationalised in Chapters 5 and 6, and to a lesser extent in Chapters 7 and 8. The framework not only provides detailed information on the *structure* of the environment-economy system in Auckland Region, but also provides the starting basis for the dynamic modelling undertaken in Chapter 11 and Appendix B.

4.1 Why Build Static Models?

A key characteristic of many formal models is that they are static in nature. Static models are normally used to understand the functioning of a system at a particular point in time.[81] For example, a static model would be used to answer questions like: 'how many people were employed directly and indirectly by the business services industry in Auckland Region in 2001?' or 'what was the level of residential water use in Auckland Region in 1998?' In this way, static models are independent models in their own right (Hicks, 1985; Ruth and Hannon, 1997). There are several reasons why we would want to build a static model of the Auckland Region:

[81] When considering time, economists crudely characterise models as static, comparative static, dynamic and comparative dynamic.

- *Determining system state.* A static model can yield theorems about "the values of ... variables ... in a state of rest" (Kuenne, 1963, p.14). Thus, static models focus on state rather than on the process of change.
- *Setting initial conditions.* By capturing state, static models may be used to set initial conditions for dynamic models (Ford, 1999). Similarly, static models may be used to establish baselines or benchmarks, or validate dynamic models.
- *Comparative statics.* Static models may be extended to formulate theorems about changes in the values of variables "between two states of rest" (Kuenne, 1963, p.14) or before and after change[82] (Baumol, 1970; Fisher, 1983).
- *Analytical ease of use.* Static models yield single solution vectors, compared with dynamic systems where "a set of such vectors is linked in a path through time" (Kuenne, 1963, p.14).
- *Structural analysis.* The main advantage of static models is that they provide detail on the structure of the system being considered (see below).

Static analysis, and in particular structural analysis, of economic and ecological systems is not however a new idea. Regional economists, for example, have used input-output analysis (Richardson, 1972; O'Connor and Henry, 1975; Leontief, 1985; Lonergan and Cocklin, 1985; Miller and Blair, 1985) to study in detail the structural make up of their economies including identification of key economic interdependencies, the economic consequences of financial injection (e.g. infrastructure construction, major tourist event *etc.*), patterns of production and consumption, and trade analysis. Similarly, ecologists have studied structural relationships using methods such as network analysis (Hannon, 1973b), ascendency indices (Ulanowicz, 1991), energy analysis (Hannon, 1973a, 1979, 1982, 1991; Hannon *et al.*, 1984), and environs analysis (Patten, 1981, 1982). Moreover, authors such as Isard (1972, 1975) and Victor (1972a, 1972b) have extended input-output analysis to study the structural make up of integrated ecological-economic systems.

Careful consideration and caution must, however, be given to the findings of any static analysis. In a temporal sense, static models are closed, permitting the functioning of a system to be examined without any reference to that which is going on outside it (Hicks, 1985). Interpretation of static analysis therefore requires one to assume that the system is in, or near, equilibrium (Baumol, 1970; Fisher, 1983). Of course, this means that no planning has taken place, or possibly could take place, within the system that could influence any possible future

[82] For example, a comparative static model of Auckland Region's economy could answer questions such as 'what was the annual trend of employment in business services between 1987 and 2004?' or 'how much land was used by the mining and quarrying industry in 2001 and 2003?'

state of the system. As Fisher (1983, p.3) puts it, "convergence to equilibrium must be sufficiently rapid that the system, reacting to a given parameter shift, must get close to the predicted new equilibrium before parameters shift once more". In other words, for static models to be useful, the temporal variables that have been assumed to be static with the period of study must also remain relatively static in the real world.

Many real world systems, including the Auckland Region environment-economy system, are characterised by constant change resulting from the presence of feedbacks, time lags and the like associated with investment, construction, climatic conditions and so forth. In the context of understanding how the Auckland Region environment-economy system functions, temporal implications associated with human perturbation or stochastic environment change are dealt with in Chapters 11 and Appendix B of this thesis.

4.2 Input-Output Analysis as the Basis for an Integrated Environment-Economy Systems Framework

The pathway pursued here in the development of an integrated environment-economy systems framework for the Auckland Region is based on input-output analysis. Input-output analysis, developed by Wassily Leontief during the 1930s, provides a comprehensive snapshot of the *structure* of inter-industry linkages in an economy. Most developed nations prepare input-output tables at regular intervals. Generally speaking, an input-output table of a nation is conceptually reconcilable with its system of national accounts (SNA). In addition, input-output tables adopt internationally recognised systems of commodity/industry classification (e.g. the Central Product Classification (CPC), International Standard Industrial Classification (ISIC), and the Harmonised System (HS)). This facilitates comparison across space and through time.

Although input-output tables (models)[83] are usually presented in financial terms, authors such as Daly (1968), Isard (1968), Kneese *et al.* (1970), Leontief (1970) and Victor (1972a) *inter alia* have demonstrated that biophysical information on resource use and generation of residuals (i.e. waste, pollution, emissions *etc.*) may also be placed in an input-output framework. More recently, analysts such as Stahmer *et al.* (1996, 1997, 1998) and Gravgård (1998) have

[83] An input-output table is no more than a numerical description of the flows in an economy, in tabular form. These numbers (in the 'Table') can be readily converted into: (i) mathematical *matrices* (and vectors). Matrices are mathematically rectangular arrays of elements, set out in rows and columns, that facilitate the solution of mathematical problems; (ii) mathematical *models* which are systems of simultaneous linear equations of the interdependencies (flows) in the economy. The author has attempted to distinguish between input-output 'tables', 'matrices' and 'models' in this thesis, but sometimes the terms can be used interchangeably. Appendix A contains a description of how input-output tables can be converted to corresponding 'matrices' and 'models'.

generated national physical input-output tables. Along these lines, an input-output approach may be used to assess Auckland Region's environment-economy system. Moreover, there are several reasons for the adoption of an input-output approach:

- *It is a comprehensive method.* It provides a detailed decomposition of the structural relationships in an entire economy. This includes complete coverage, albeit through aggregation, of the types of commodities produced, of the production processes used, and of final consumption within an economy.
- *It is a systematic method.* Input-output matrices provide a convenient checklist to ensure that all flows are taken into account. The conservation principle (i.e. inputs equalling outputs) of input-output accounting further ensures that there are no unintentional blind spots.
- *It avoids common methodological pitfalls.* Input-output analysis avoids double counting, particularly when dealing with complicated networks of indirect flows that have significant feedbacks, and joint production problems when allocating multiple outputs of commodities from a single economic process.
- *It is a mathematically rigorous method.* The use of matrix algebra is not only efficient in dealing with large computationally complex datasets, but also enables analysis to be undertaken in an internally consistent mathematical framework. Using input-output mathematics, it is possible to calculate first, second, third ... n^{th} round (i.e. infinite regress) effects accurately and comprehensively.
- *It is easily extended.* Input-output models may also be utilised in short run comparative static analysis, for example, to study the implications of policy change, economic growth, population change, capital investment, trade and so on. Furthermore, the distributional impacts of change may also be traced with extensions to the basic framework, including socio-economic effects (e.g. Economic Impact Assessment, Social Accounting Matrices) and price change (as an input into Computable General Equilibrium Modelling).

A brief description of the mathematics of input-output analysis along with its most critical assumptions is provided in Appendix A – full details may be found in Richardson (1972), O'Connor and Henry (1975), Leontief (1985) and Miller and Blair (1985).

4.3 Critical Review of Environmental Input-Output Modelling

Environmental input-output models modify and extend the conventional input-output framework to include resource use and residual (i.e. waste, pollutant and emission) generation.

A key feature of environmental input-output modelling is that it is principally concerned with the environment-economy interface; in particular, how changes in the economy might impact on the environment (e.g. resource provision/scarcity, residual generation, and the costs of substitutes/abatement) or *vice versa.* Authors such as Miller and Blair (1985) have tentatively grouped environmental input-output frameworks into three categories:

- *Generalised or augmented input-output models.* These are typically formed by adding rows and columns, representing pollution generation and abatement activities[84], to a technical coefficients matrix. A matrix of pollution or abatement coefficients, P, is defined where each element, P_{kj}, represents pollutant k generated per dollar of output of industry j. Multiplying P by the Leontief Inverse yields the direct and indirect pollution, P^*, produced per unit of final demand generated in industry j i.e. $P^* = P(1 - A)^{-1}Y$. Although simple, this approach can provide valuable insight into the magnitude of the indirect environmental impacts associated with changes in economic activity.
- *Inter-industry input-output tables.* These models extend the basic inter-industry framework to include an environment sector, under which the use and production of ecological commodities is recorded (Miller and Blair, 1985). Several examples of inter-industry economic-ecological models, as discussed below, include Cumberland (1966), Daly (1968), Ayres and Kneese (1969) and Leontief (1970).
- *Commodity-by-industry models.* Such models treat resource use and residuals production as commodities in the form of a commodity-by-industry framework. The key difference between a commodity-by-industry and an industry-by-industry model is data is compiled at a commodity level rather than industry level which aggregates to form homogeneous outputs. Thus, multiple outputs per industry are permitted. Examples of commodity-by-industry models, as discussed below, include Isard (1968, 1972, 1975), Victor (1972a, 1972b) and the recent Physical Input-Output Tables (Models) developed by Stahmer *et al.* (1996, 1997, 1998) and Gravgård (1998).

[84] Resource requirements have also been determined e.g. for energy (Gilliland, 1975; Hannon, 1979; Costanza, 1980; Giampietro and Pimentel, 1991), water (Hite and Laurent, 1971, 1972; McDonald and Patterson, 1998) and land (Bicknell *et al.* 1998; Ferng, 2001; McDonald and Patterson, 2004).

4.3.1 Inter-Industry Environmental Input-Output Models

4.3.1.1 Cumberland Model[85]

Cumberland (1966) is generally acknowledged as the first to develop an environmental extension of input-output analysis.[86] In order to incorporate production of externalities into the analysis of alternative regional development strategies, Cumberland (1966) argued that additional rows and columns could be augmented to a conventional input-output matrix to accommodate environmental costs and benefits associated with economic activity.

The Cumberland model is shown in Figure 4.1. Rows *Q* and *C* respectively record in financial terms the environmental benefits and costs associated with each industry and final demand category for a given development programme. As a minimum, Cumberland suggests that each development program cover water, air, open space and possibly aesthetics and personal safety. The net environmental benefit row *R* records the difference between rows *Q* and *C*, while the column vector *B* measures the costs, by industry, of restoring the environment to its pre-development state.

[85] This Section outlines a various environmental input-output 'models'. Strictly speaking, these descriptions are of 'tables' as generally there is no matrix or equation structure specified – the exception being Section 4.3.1.4 (for the Leontief model). However, the author uses the term 'models' as there is an implicit linear equation structure even though it is not explicitly specified.

[86] Herfindahl and Kneese (1965) had however previously described the resource/environment interface from an economic perspective in a framework comparable with an input-output table.

	Industry 1	Industry ...*j*...	Industry *n*	Sub Total	Household Consumption	Government Consumption	Other Final Demands	Exports	Sub Total	Total Gross Output	Environmental Balance *B*
Industry 1											
Industry ...*i*...		Quadrant I				Quadrant II					B_i
Industry *n*											
Sub Total											
Labour											
Value Added		Quadrant III				Quadrant IV					
Other Primary Inputs											
Imports											
Sub Total											
Total Gross Input											
Environmental Benefits (+) *Q*											
Environmental Costs (-) *C*											
Environmental Balance R=(Q-C)		R_j									

Figure 4.1 Cumberland Model. Adapted from Cumberland (1966, p.68).

One criticism of this approach is difficulties exist with the non-market valuation[87] of environmental costs (e.g. restoration) and benefits. A further deficiency of the Cumberland model is that it ignores the flows from the environment into the economy and *vice versa.* Richardson (1972, pp.218-219) suggests that this is because "Cumberland intends his extended input-output model to be used as an aid to a goal-oriented regional policy or development programme and not as a general inter-industry analytical tool". Richardson (1972) also asserts that the Cumberland model more closely resembles a cost benefit evaluation than an input-output table. Therefore it can be argued that the Cumberland model suffers from all of the shortcomings of cost benefit analysis as outlined by authors such as Blamey and Common (1994), Norton (1995), More *et al.* (1996) and Kahn (2005).

[87] This includes the well known limitations of non-market valuation techniques such as contingent valuation, hedonic pricing, willingness to pay, replacement cost methods and willingness to accept compensation (refer to Kahn (2005, pp. 92-128) for further details).

4.3.1.2 Daly Model

Daly (1968) proposed a highly aggregated model of the environment-economy interface based on an industry-by-industry framework (Figure 4.2). The model is divided into two domains: human and non-human. Conventional economic activities, such as agriculture, industry and households, are categorised under the human domain, while biophysical/ecological processes are classified within the non-human domain. The biophysical processes are further subdivided into living (animal, plant and bacteria) and non-living (atmosphere, hydrosphere and lithosphere) transformers of matter-energy. Interdependence between processes within the human and non-human spheres is portrayed respectively in Quadrants I and IV. Quadrant III represents the reverse flow of 'free goods' (e.g. resource inputs) while Quadrant II depicts the flow of externalities (e.g. residuals) between the human and non-human spheres. Mixed financial and physical units are utilised to describe the flows.

		Human			Non-Human							
		Agriculture	Industry	Household (final consumption)	Animal	Plant	Bacteria	Atmosphere	Hydrosphere	Lithosphere	Sink (final consumption)	Total
Human	Agriculture Industry Household (final consumption)	Quadrant I			Quadrant II							
Non-Human	Animal Plant Bacteria Atmosphere Hydrosphere Lithosphere Sun (primary services)	Quadrant III			Quadrant IV							

Figure 4.2 **Daly Model.** Adapted from Daly (1968, p.402).

Not satisfied with a purely descriptive tool, Daly proposed the calculation of technical coefficients by dividing each row element by its corresponding row total. This approach has however been criticised on the grounds that the economic and ecological commodities cannot be totalled as they are expressed in different units. According to Victor (1972a, p.41) these row totals are meaningless, "despite Daly's unsubstantiated claim that 'there appear to be no theoretical problems in extending the input-output model in this way'".

Daly's adoption of an industry-by-industry framework for analysing environment-economy interactions results in a number of additional complications. Firstly, the homogeneity assumption is illogical when transferred to the non-human (ecological) domain because aggregation of different ecological commodities is not possible due to the absence of a consistent numeraire. Secondly, in the adoption of non-comparable units the model tries to commensurate ecological commodities, which have no price, with economic commodities which do. Thirdly, the linearity assumption converts many non-linear ecological interdependencies to a linear nature. And finally, the assumption of fixed proportions of inputs is not necessarily valid when considering ecological interrelationships.

4.3.1.3 Ayres-Kneese Model

Ayres and Kneese (1969) developed an extended inter-industry model incorporating resource use, residuals, pollutant abatement and recycling. A key feature of the model is that it invokes the 'materials balance principle' i.e. mass and energy must be conserved across the model. The Ayres-Kneese model is depicted in Figure 4.3. Coefficients in the extraction matrix I, and production matrix II, form a conventional inter-industry input-output matrix. These coefficients represent the fractional inputs per unit of output, as measured in pecuniary terms, of each industry. The coefficients in the abatement matrix III represent the actual costs of abatement. Additionally, matrices representing resource inputs, *R*, and residual outputs, *W*, are also incorporated.

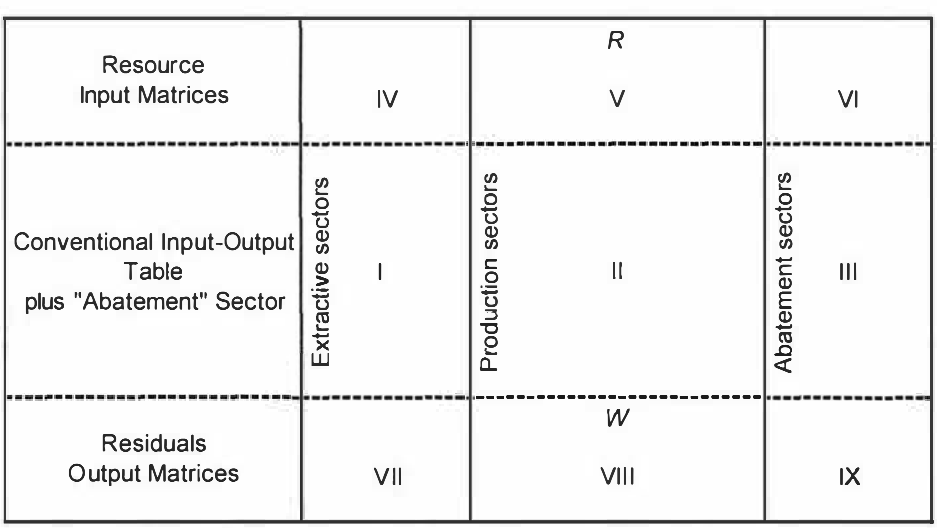

Figure 4.3 **Ayres-Kneese Model.** Adapted from Ayres (1978, p.118).

The resource inputs matrix R is further separated into three sub matrices IV, V and VI. Each sub-matrix has one row for each resource and one column of each industry identified in the input-output matrix. Each coefficient in matrix R records the resource input (in physical units) per unit of output (in pecuniary terms) of a given industry[88] (Ayres, 1978). Obviously, resource use is mostly undertaken by the extraction sectors (sub-matrix IV), while the vast majority of entries in the upper sub-matrices V and VI are zero – notable exceptions would include oxygen for combustion and residuals for reuse or recycling.

The resource output matrix W, like the resource input matrix, R, has three sub-matrices VII, VIII and IX. Each sub-matrix has one row for each pollutant and one column for each industry of the input-output table. Each coefficient in the W matrix records residual output, in physical units per pecuniary unit of output in a given industry. Columns of the extraction sub-matrix, VII, represent gross residuals by industry, while the columns of the production matrix, VIII, record the gross production of residuals by industry. Abatement is recorded in sub-matrix IX. The entries in this matrix represent the net amount of residuals and are typically negative.

Overall, the Ayres-Kneese model extends the conventional input-output model to include resource use, residual production and abatement. A key aspect of the model is that it instigates the materials balance principle ensuring conservation of mass/energy for the system under study. The model also captures flows across the resource use-economy, and economy-residual, interfaces. One additional advantage is that it can track abatement from one environmental medium to another.

4.3.1.4 Leontief Model

Leontief (1970) has also attempted to include environmental factors into an inter-industry framework. His approach is to extend the input-output model by one additional industry representing pollution abatement – the column measuring pollution abatement in pecuniary units, the row recording pollutant output in physical terms (Figure 4.4). As the economy generates pollution this additional industry absorbs the cost of the associated pollution abatement measures. This allows the estimation of cost effects associated with mitigation technologies and the investigation of the effectiveness of possible policies that may be used to regulate pollution.

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[88] Ayres and Kneese (1969) discuss the possibility of using shadow (or virtual) prices to value the physical flows. However, after some discussion they conclude that the "total value of ... services performed by the environment cannot be calculated" (Ayres and Kneese, 1969, p.292).

Inputs and Pollutants' Output \ Output Industries	Industry 1	Industry 2	Pollution Abatement	Final Demand	Total Output
Industry 1	X_{11}	X_{12}	X_{1pa}	Y_1	X_1
Industry 2	X_{21}	X_{22}	X_{2pa}	Y_2	X_2
Physical Output of Pollutant	X_{1p}	X_{2p}	$-X_{pa}$	Y_p	X_p
Primary Inputs	V_1	V_2	V_{pa}	V_y	V
Total Inputs	X_1	X_2	X_{pa}	Y	X

Figure 4.4 **Leontief Model.** Adapted from Richardson (1972, p.221).

Since the pollutant row is measured in physical units, it is excused from any vertical summation. Instead, the gross output of the physical pollutants row is determined from the following calculation,

$$X_p = X_{1p} + X_{2p}. \quad (4.1)$$

The net output of pollutants may be obtained in the following manner.

$$X_p = X_p - X_{pa}. \quad (4.2)$$

By substitution

$$X_p = X_{1p} + X_{2p} - X_{pa}. \quad (4.3)$$

At the intersection of the pollutant abatement column industry, and the physical pollutants row, is an entry, $-X_{pa}$, that represents the physical amount of pollutants eliminated by the pollution abatement column industry. This output is also expressed in financial terms as the total input entry at the bottom of the pollution abatement column, X_{pa}. This double valuation of the output of the pollution abatement industry allows direct estimation of the financial cost associated with eliminating each unit of pollution.

Leaving aside the physical pollutants row allows simple accounting identities of the Leontief model to be represented algebraically,

$$X = X_1 + X_2 + V = X_1 + X_2 + X_{pa} + Y \qquad (4.4)$$

Thus $V = Y + X_{pa}$ (4.5)

$\therefore$ $Y = V - X_{pa}$. (4.6)

With the inclusion of the pollution abatement industry it can be seen from Equation 4.6 that the conventional input-output identity of final demand equating to value added is not preserved, i.e. $Y \neq V$. The absolute difference between final demand and value added is a measure of the pecuniary expenditure on pollution abatement. Furthermore, the absence of a pollution abatement row industry infers that this expenditure is absorbed completely by households. In other words, intermediate demand industries do not purchase inputs from the pollution abatement industry.

A primary criticism of the Leontief model is that the pollution abatement is recorded twice – physically in the pollutants row, and monetarily in the pollutants column. This double valuation is required so that the financial costs of eliminating each unit of pollution may be estimated. It is however undertaken without any consideration of the materials balance principle. Adherence to the materials balance principle is impossible as only flows from the economy to the environment are modelled, i.e. resource use is not considered.[89] A further criticism is the Leontief model applies non-market valuation techniques to derive the pollutants column (in financial terms) – refer to Kahn (2005, pp.92-128) for detailed limitations of using non-market valuation techniques.

4.3.2 Commodity-by-Industry Environmental Input-Output Models

This Section covers models that have a commodity-by-industry structure, thereby allowing for multiple commodity outputs per industry. These models include the Isard (1968), Victor (1972a, 1972b) and Physical Input-Output Tables (Stahmer *et al.*, 1997).[90]

[89] The ramifications of recycling and waste treatment prior to discharge are also not considered.

[90] The Isard model is strictly a commodity-by-industry, as directly reflected in its matrix structure – commodities (rows) by industries/processes (columns). Both the Victor and Physical Input-Output Tables are arguably not strictly commodity-by-industry models. Although the Victor model quadrants do have either a commodity-by-industry or a industry-by-commodity structure to them, the overall model is not commodities (rows) by industries (columns). The same is the case for the Physical Input-Output Tables.

4.3.2.1 Isard Model

Between the late 1960s and mid 1970s Walter Isard and associates constructed several ecologic-economic input-output models. This included the notable Plymouth Bay, Massachusetts regional planning study of the environmental repercussions of a marina development. The Isard model, like the Daly model, recorded interactions within and between the environment and economy in a comprehensive manner. The Isard model, however, relied on coefficients taken directly from scientific literature, while the Daly model proposed to derive such coefficients through accounting identities.

The Isard model is illustrated in Figure 4.5. The model is divided into quadrants with entries in coefficient format – negative coefficients representing inputs and positive coefficients representing outputs. Quadrants I and IV describe flows respectively within the economy (i.e. goods and services) and the environment (i.e. energy and mass). Quadrant I, the inter-industry coefficients matrix, is a commodity-by-industry technical coefficients matrix. Unlike conventional industry-by-industry models, where only one homogeneous output per industry may be produced, Isard's commodity-by-industry model permits multiple outputs per industry. Quadrant IV, the interprocess coefficients, records ecological interdependence between various ecological processes in terms of ecological commodities. Classification of the commodities and processes was based on an ecological taxonomy consisting of abiotic (i.e. meteorological, geological, physiological, hydrological and soil types) and biotic (i.e. plant and animal life) groupings. In this way, detailed information on food chains, food webs and biogeochemical cycling was included in the model.

		Economic Industries	Ecologic Processes
		Industry 1 Industry ...*j*... Industry *n*	Process 1 Process ...*p*... Process *m*
Economic Commodities	Commodity 1 Commodity ...*i*... Commodity *n*	Quadrant I - Economic System: Intersector Coefficients	Quadrant II - Ecologic Processes: Their Input and Output Coefficients re Economic Commodities
Ecologic Commodities	Commodity 1 Commodity ...*c*... Commodity *m*	Quadrant III - Economic Sectors: Their Input and Output Coefficients re Ecologic Commodities	Quadrant IV - Ecologic System: Interprocess Coefficients

Figure 4.5 **Isard Model.** Adapted from Isard (1968, p.87).

Quadrants II and III depict flows between the economy and environment. The upper right hand corner, Quadrant II, shows the production and use of economic commodities by ecological processes. It is worth noting that coefficients in this quadrant generally reveal that very few economic commodities flow directly from the environment as delivered goods for consumption by final demand categories. Quadrant III records the use of ecologic commodities by industries as well as the export of ecologic commodities from industries to the environment. These coefficients, as in Quadrant II, are expressed in terms of the ecological inputs to, and outputs from, the economic system per unit of economic output.

Critics such as Victor (1972a), Johnson and Bennett (1981) and Lonergan and Cocklin (1985) point to practical difficulties associated with obtaining appropriate data for the complex ecological interprocess coefficients in Quadrant IV. Isard (1975, p.343) recognised this, stating that "the set of data pertaining to the environmental system which we inherit today is tremendous in variety and amount ... We therefore confront difficulty in trying to develop a systematic input-output description of the ecologic system". Isard (1968) also comments on the restrictiveness of the linearity assumption suggesting that those ecological processes that are non-linear in nature should be considered outside of the input-output framework. A further concern is that it implicitly assumes that environmental resources remain stable over time when, in actuality, changes in resource quality could affect the invariant nature of coefficient relationships (Kapp, 1970; Richardson, 1972). Despite these assumptions, the Isard model is conceptually very attractive. Steenge (1977, p.97) argues that the work of Isard "will remain indispensable mainly because here the line separating theory and implementation was crossed definitively."

4.3.2.2 Victor Model

Victor (1972a, 1972b) developed a commodity-by-industry input-output model of the Canadian economy to analyse planning problems from an environmental perspective. Realising the conceptual strength of the Isard model, but also the difficulty associated with accurately populating the model's Quadrant IV, Victor sought out a compromise between theoretical ideal and empirical implementation. The resulting model, displayed in Figure 4.6, focuses on comprehensively recording economic-ecologic linkages, but ignores the within environment flows, arguing that data paucity would make a full implementation near impossible.

		Economic Commodities	Industries	Final Demand	Totals	Ecological Outputs		
						Land	Air	Water
Economic Commodities			*A*	*B*	*c*		*G*	
Industries		*D*			*e*		*F*	
Primary Inputs			*H*	*K*	*l*			
Totals		*c'*	*e'*	*o'*	*p*		*q'*	
Ecological Inputs	Land							
	Air	*S*	*R*		*t*			
	Water							

Figure 4.6 **Victor Model.** Adapted from Victor (1972a, p.56). Quadrants with no symbols in them represent null matrices i.e. matrices containing only zero elements.

The accounting framework used by Victor is essentially a commodity-by-industry matrix, in Stone's (1961, 1966) supply-use format, appended with additional rows and columns respectively representing ecological inputs and outputs. Economic transactions are represented in financial terms, while entries in ecological sectors are expressed in physical units. The ecological commodities that constitute the ecological sector are classified under three headings: land, air and water. In addition to the conventional input-output accounting identities, Victor defines several ecological accounting identities based on the materials balance principle.[91]

Using this framework Victor developed a series of analytical models relating economic production to effects on the environment in terms of resource use and residual generation. First, he created a set of ecological impact matrices, with and without import leakages. Second, by using shadow prices to represent the social valuation of ecological commodities, he outlined a procedure for using the impact matrices to derive estimates of ecological costs of producing and consuming economic commodities. And third, he disaggregated the estimates of ecological inputs and outputs by province, adding a valuable spatial dimension to his model.

4.3.2.3 Physical Input-Output Tables

Physical Input-Output Tables (PIOTs) not only trace the physical flow of commodities through the environment, but also between the environment and the economy and *vice versa* (Stahmer *et al*.,. 1997). A cornerstone of the PIOT framework is adherence to fundamental physical principles, particularly materials and energy balance as required by the first law of thermodynamics. PIOT accounting is a recent phenomenon.[92] Katterl and Kratena (1990) are credited with pioneering the first PIOT – a partially complete table of the 1983 Austrian economy (Strassert, 2000). Old Länder, a PIOT of the 1990 West German economy, was the first complete and official table to be constructed (refer to Stahmer *et al.* (1996, 1997, 1998)). Several other PIOTs have followed, including an official table for the 1990 Danish economy (Gravgård, 1998), and less ambitious unofficial efforts for Italy (Nebbia, 1999) and the United States (Acosta, 2000).[93]

A PIOT is typically presented in a tabular commodity-by-industry format with production processes (industries) described by their material inputs and outputs in physical units i.e. tonnes (Figure 4.7). Each input is described by its industrial origin (or as imports), while each output is

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[91] This assumes that the model is a closed economy and there is no accumulation of mass in the economy itself (Victor, 1972a).

[92] The roots of physical accounting can be traced back much further. Strassert (2000) identifies two main analytical strata, namely, production theory and national accounting. The former stratum is based on the physical economy-environment work of Georgescu-Roegen (1971, 1979a, 1984) and Perrings (1987), and the latter stratum on Stahmer (1988, 1993), the United Nations (1993a, 1993b), Radermacher and Stahmer (1996) and Stahmer *et al.* (1996, 1997, 1998). Underpinning these strata is the earlier material/energy balance work of Ayres and Kneese (1969), Kneese *et al.* (1970), Ayres (1978, 1993b) and more recently the Material Flow Accounting efforts of *inter alia* Bringezu (2000).

[93] The only regional attempt to develop a PIOT appears to have been undertaken by Baden-Württemberg (1990, cited in Strassert (2000)) for Bundesland in Germany.

explained by its destination i.e. industry, final consumption or exports (Strassert, 2000). Strassert (2000), in his description of the German PIOT, uses five matrices to describe physical flow. Matrix I, the intermediate production matrix, describes physical flow within the economic system. Matrix IIA describes the final consumption of physical commodities by households *etc.*, while any residuals (i.e. waste, pollutants and emissions) produced in production or consumption are described in Matrix IIB. Similarly, Matrices IIIA and IIIB respectively describe the use or conservation of material funds[94], and the use of natural resources (i.e. renewable, non-renewable and recycled) supplied by the environment as an input into the production process.

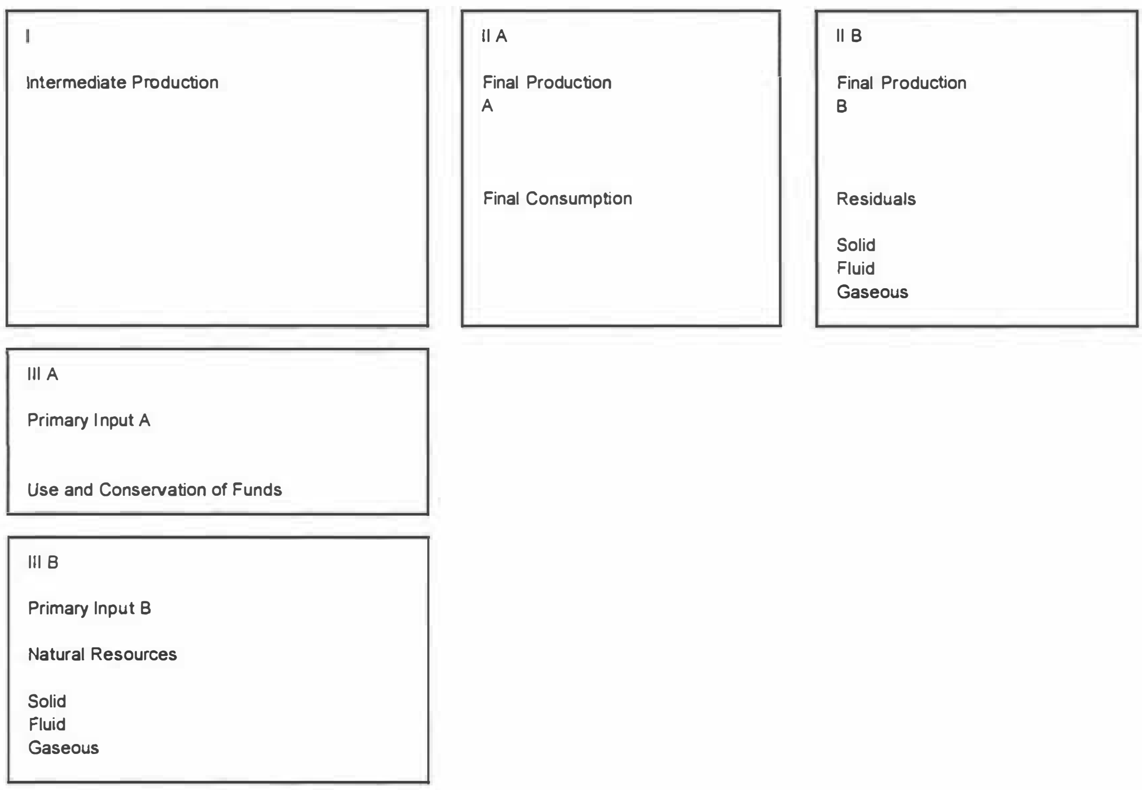

Figure 4.7 A Physical Input-Output Model. Adapted from Strassert (2000, p.3).

Unlike a conventional input-output model which focuses on the structural nature of economic transactions (Matrix I), final consumption by households and exports (Matrix IIA), and particularly the contribution made by each production process to value added (Matrix IIIA), a PIOT tends to focus instead on the structural nature of economic transactions (Matrix I), resource use (Matrix IIIB), residual production (Matrix IIB) and particularly on the completeness of materials balance. Moreover, the PIOT is conceptually consistent with the ideas of authors such as Boulding (1966) and Daly (1991) who view economic production as a

[94] Value added components such as labour and capital are conceived of as funds or agents transforming the flow of natural resources into flows of products (Daly, 1995).

subsystem encapsulated within a finite and non-growing environment. This conceptualisation implicitly captures the role played by economics in extracting/harvesting low entropy matter-energy and ultimately producing high entropy matter-energy. Consequently, this one-way flow beginning with resources and ending with residuals can be thought of as the digestive tract of an open biological system connected by the environment at both ends (Daly, 1995).

4.4 Static Systems Framework Used in this Research for the Auckland Region

The focus of the remainder of this Chapter is on developing a static systems environment-economy framework for the Auckland Region. This framework provides a comprehensive, consistent and robust analytical mechanism for quantifying the linkages between the Region's economic activity and its biophysical environment. The detailed methodological steps used in development of this framework, and the analytical findings related to Auckland Region, are described in Chapters 5, 6 and 7.

4.4.1 Conceptualisation of the Environment-Economy System

In its simplest form Auckland Region's environment-economy system may be conceptualised as an economy connected to its surrounding environment via material and energy flows. The Auckland Region does not however exist in isolation, but rather interfaces with various other environment-economy systems. The Auckland Region environment-economy system, and its relationship with other systems, is depicted in Figure 4.8.

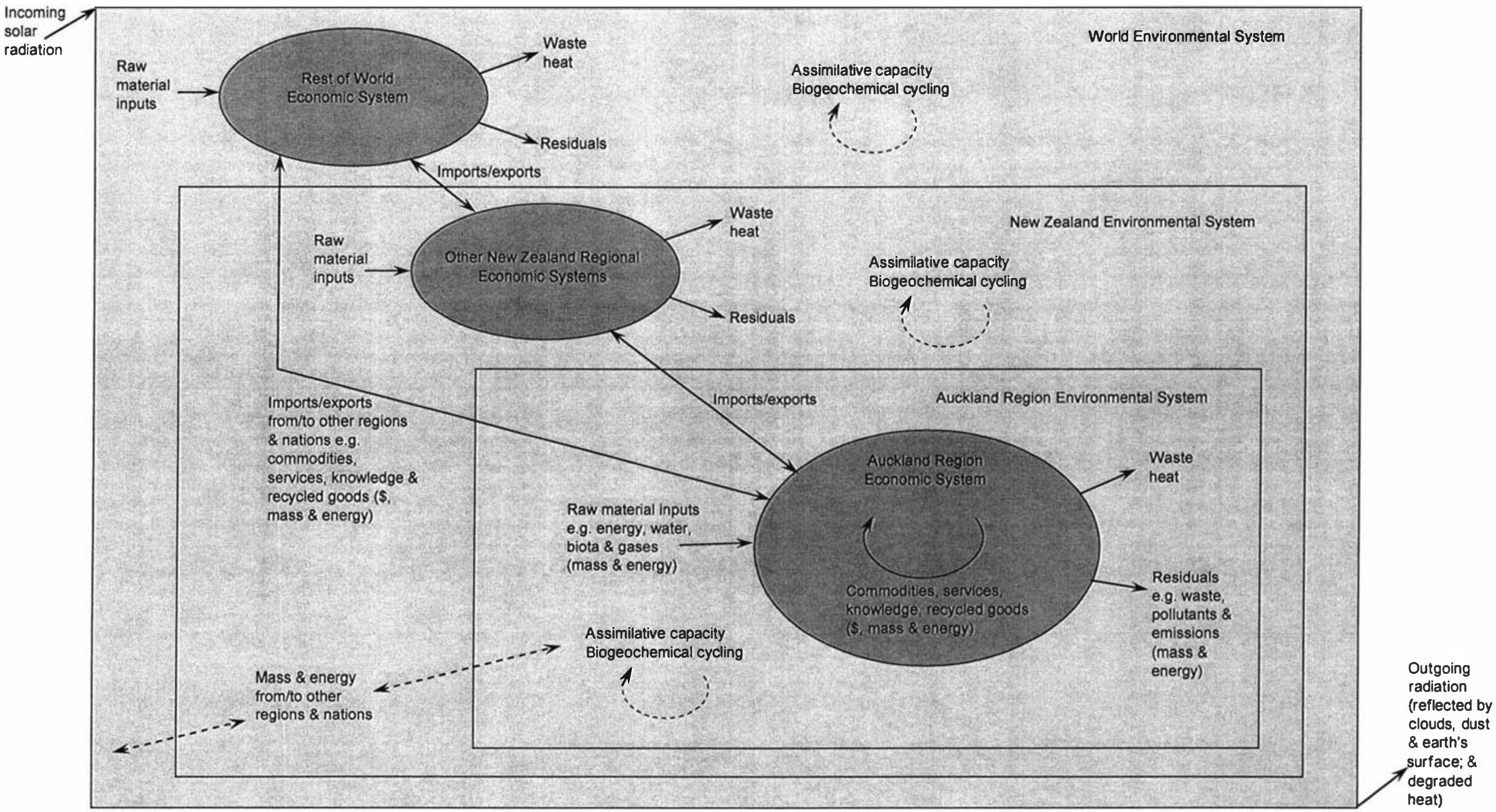

Figure 4.8 **Auckland Region's Environment-Economy System and its Relationship with Other Systems**

4.4.1.1 System Boundaries

System diagrams are used to define the Auckland Region environment-economy system, its relationship with other systems, and to identify the key flows and influences between these systems. Oblongs are used to delineate environmental system boundaries, while an elliptical interface is used to separate an economy from its environment. These system boundaries are based on an ecological-economic world view.[95]

Environmental Systems (Denoted by light shading on Figure 4.8)

A nested hierarchy is used to represent the Auckland Region, New Zealand and World environmental systems. The Auckland Region environmental system is nested within the New Zealand environmental system, which is in turn nested within the World environmental system. These environmental systems encompass all physical flows not covered by the flow of economic commodities. The geospatial boundaries of Auckland Region and New Zealand are aligned to Statistics New Zealand's regional boundary definitions.[96] This does not include any part of New Zealand's Exclusive Economic Zone (EEZ).

Economic Systems (Denoted by dark shading on Figure 4.8)

Each economic system is, according to the adopted biophysical world view, seen as a subsystem of the wider environmental system in which it resides, i.e. the Auckland Region, rest of New Zealand and rest of World economies are located respectively within the Auckland Region, New Zealand and World environmental systems. The flows contained within the economic systems are, where possible, defined according to the United Nations (1993b) SNA. This includes the flow of commodities and services produced for production[97] (i.e. intermediate demand) and to

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[95] System boundaries are almost always an artificial or abstract construct governed by a particular world view. Underpinning any world view is a set of values and beliefs. Although the framework developed here can help us to understand the implications of human-induced or stochastic change on the Auckland Region environment-economy system, it has limited ability to help us resolve any consequential ethical dilemmas that may arise.

[96] Much has been written about the appropriate selection of spatial boundaries. In ecological footprinting, for example, Wackernagel and Silverstein (2000) argue for political or cultural boundaries as they represent the level at which environmental policy or decision making most often occurs. By contrast, van den Bergh and Verbruggen (1999) dispute such boundaries on the grounds that they have no environmental meaning, favouring instead hydrological, climate zone or larger connected ecosystem boundaries. In this thesis, Statistics New Zealand's Auckland Regional Council boundary is used, which reflects both political (i.e. as the principal agency involved in regional environmental governance) and geographic (i.e. river catchment) boundaries.

[97] Industries which perform this production are made up of resident establishments. In some cases these establishments may, for example, be located within the Auckland Region, but operate outside the region and *vice versa*. This may result in coding difficulties.

satisfy final demand (i.e. domestic household consumption and exports), temporarily stored in physical stocks, or used as capital for production (i.e. accumulation).

Patterson (2002b, p.21) argues, from a similar biophysical worldview, that several important sustainability issues arise from the above conceptualisation:

- *The extent to which the economy occupies the biosphere space.* Estimates by Vitousek *et al.* (1986) indicate that the economy has appropriated 40 percent of the Net Primary Productivity of the terrestrial biosphere. The ultimate physical limit cannot exceed 100 percent and certainly, to have a safety margin, it has been argued that realistically this limit could be more like 80 percent.
- *The extent to which the sustainability of an economic system depends on its surrounding environmental system as a source of raw material inputs.* Many raw material inputs are clearly finite and depletable e.g. fossil fuels, minerals, land and so on. Economic growth cannot be sustained indefinitely if these resources are depleted or degraded.
- *The extent to which the sustainability of an economic system depends on the sink functions of its surrounding environmental system.* Often the environmental system is relied on to efficiently purify and absorb economic residuals. There are however critical thresholds beyond which the environmental system cannot cope e.g. eutrophication of a lake, or at a global level the warming resulting from the environmental system's inability to absorb greenhouse gas emissions.
- *Critical limits exist that make complete recycling of material residuals a physical impossibility.* The Second Law of Thermodynamics tells us that degraded energy outputs can never be recycled – it has also been argued that the degree to which we may recycle materials is also limited.[98]

4.4.1.2 System Flows

A critical step in conceptualising Auckland Region's environment-economy system is to establish clearly the types of flows that exist within the various economic and environment systems, and between these systems. Nevertheless, before these flows are established it is useful to identify the types of media through which these flows take place.

[98] Refer to Chapter 2 for further details.

Flow media

There are four primary media[99] through which flows take place in the Auckland Region environment-economy framework:

- *Raw material inputs.*[100] These comprise natural resources[101] (e.g. mineral, energy, soil, water and biota) and inputs from ecosystems[102] (e.g. gases needed for combustion). Natural resources traded on a market become commodities – see below.
- *Residuals.* These include solid waste, liquid pollution and gaseous emissions. Residuals may, or may not, circulate in an economy (i.e. through recycling or reuse) for some time, but are ultimately, at some point in time, discarded to the environment.[103]
- *Commodities.*[104] These comprise goods and services that are traded on financial markets. Commodities are grouped according in the Australia New Zealand Standard Commodity Classification (ANZSCC).
- *Ecosystem services.* These are services provided by the environment that are critical to our very existence. They include services that provide environmental regulation functions such as biogeochemical cycles and other biosphere processes (providing clean air, water, soil and biological control), habitat functions (e.g. refuge and reproduction habitat), and information functions (e.g. opportunities for reflection, spiritual enrichment, and cognitive development).

Environmental System Flows

The 'white space' labelled 'Biogeochemical cycling' and denoted by the broken lines represents a complex mix of biogeochemical processes that cycle materials and energy (refer to Figure 4.9 for an expanded view of Auckland Region's environmental system). Such feedbacks may cleanse, purify and assimilate both natural materials and economic residuals. Over long time periods (often measured in geological time) they may also transform waste residuals into useful

[99] Some environment resources (e.g. land) are only used *in situ* and thus have no associated physical flow. Nevertheless, a media type may embody resources which are used *in situ*. It is therefore possible to think of a commodity flow, say for example the purchase of a burger bun, in embodied land terms.
[100] The definitions of raw material inputs and residuals provided here are based on the United Nations (1993a, 2003) SEEA system.
[101] Some natural resource flows simply represent displacement such as mining lag or water for electricity generation.
[102] It is important that ecosystem inputs be seen as distinct from ecosystem services. Ecosystem services encompass a much wider sphere of influence including biogeochemical cycling, the assimilative capacity of the environment, the provision of biodiversity and so on. Auckland Region's ecosystem services are assessed in Chapter 7 and Appendix J of this thesis.
[103] Careful classification of residuals is essential if double counting is to be avoided. Incinerated landfill waste may cause, for example, methane emissions resulting in a classification overlap.
[104] The definition provided here is based on the United Nations (1993b) SNA system.

material inputs. Nevertheless, perturbation of these cycles through economic activity may lead to more immediate consequences (e.g. eutrophication of lakes or global warming through the release of greenhouse gases) which may, in turn, affect economic systems (den Elzen *et al.*, 1995). Because these cycles are characterised by dynamic feedback loops, non-linearities and time lags the consequences of perturbing them is often unforeseen. A crude static snapshot of biogeochemical flows occurring within Auckland Region, within New Zealand and for the globe is generated in Chapter 7 and Appendix B of this thesis.

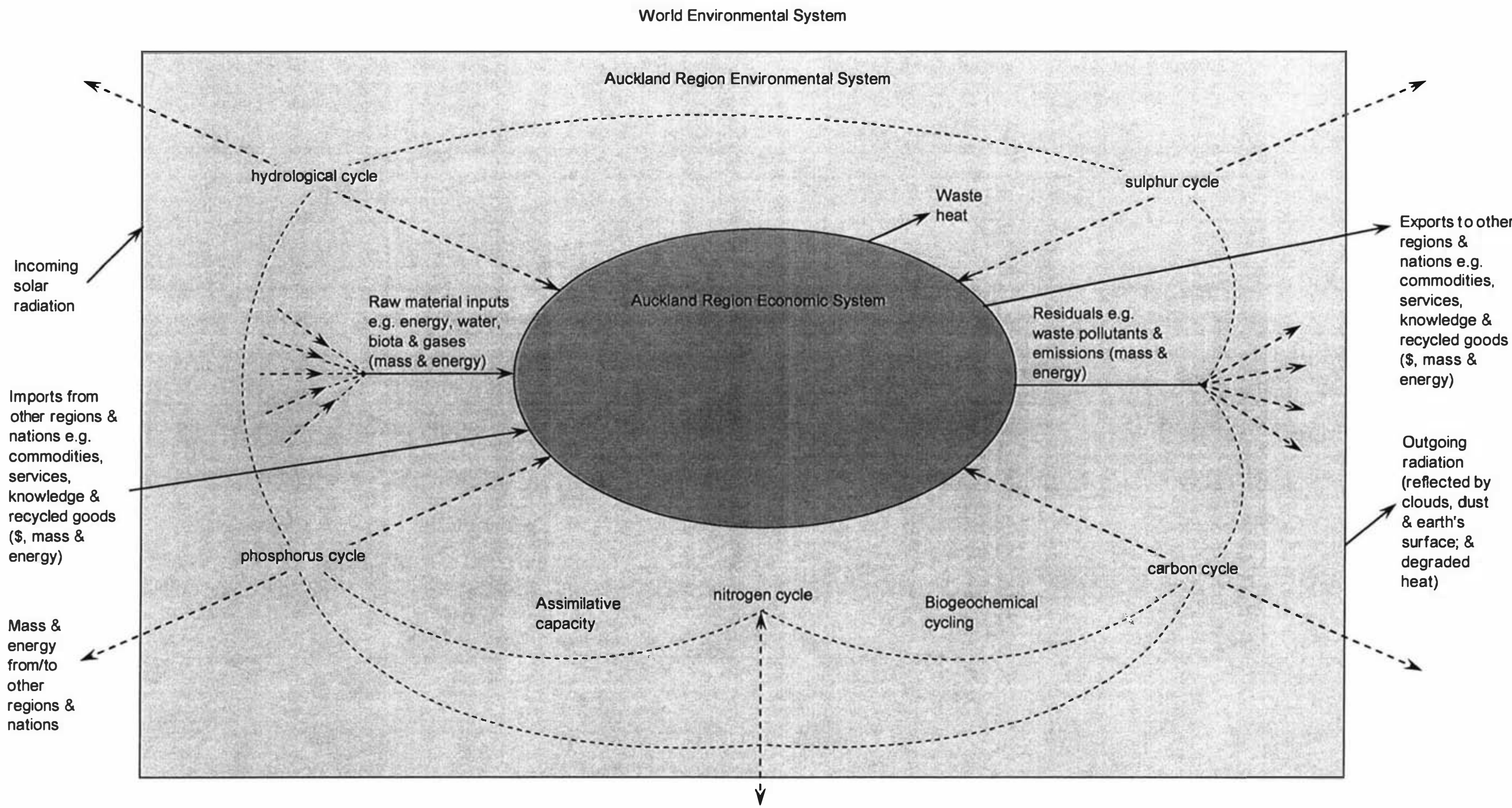

Figure 4.9 Auckland Region's Environment-Economy System With an Expanded Environmental System

Economic System Flows

The Auckland Region environment-economy system is expanded in Figure 4.10 to show clearly the types of flows that exist within the economic sub-system. Based on a conventional economic perspective, the within economic system flows may be described as follows. People provide labour, investment capital and knowledge (e.g. technology) to manufacture commodities and provide services, and are in turn rewarded with income (payments for labour/knowledge, dividends from investments) for their efforts. They use this income to purchase commodities and services (i.e. consume) or to reinvest in the economic process (i.e. capital formation). The production process involves numerous inter-industry exchanges until a final commodity/service is delivered to consumers. In this way, the economic flows are characterised by a closed loop between consumption and production (Ryan, 1995). Raw material inputs and any residuals generated receive only cursory consideration from an economic perspective. An economic snapshot of Auckland Region's and New Zealand's within economy flows is generated for the study year using a financial input-output model in Chapter 5 of this thesis.[105]

[105] Financial input-output models, both commodity-by-industry and industry-by-industry, were also developed for all of New Zealand's 74 Territorial Local Authorities and 16 Regional Councils.

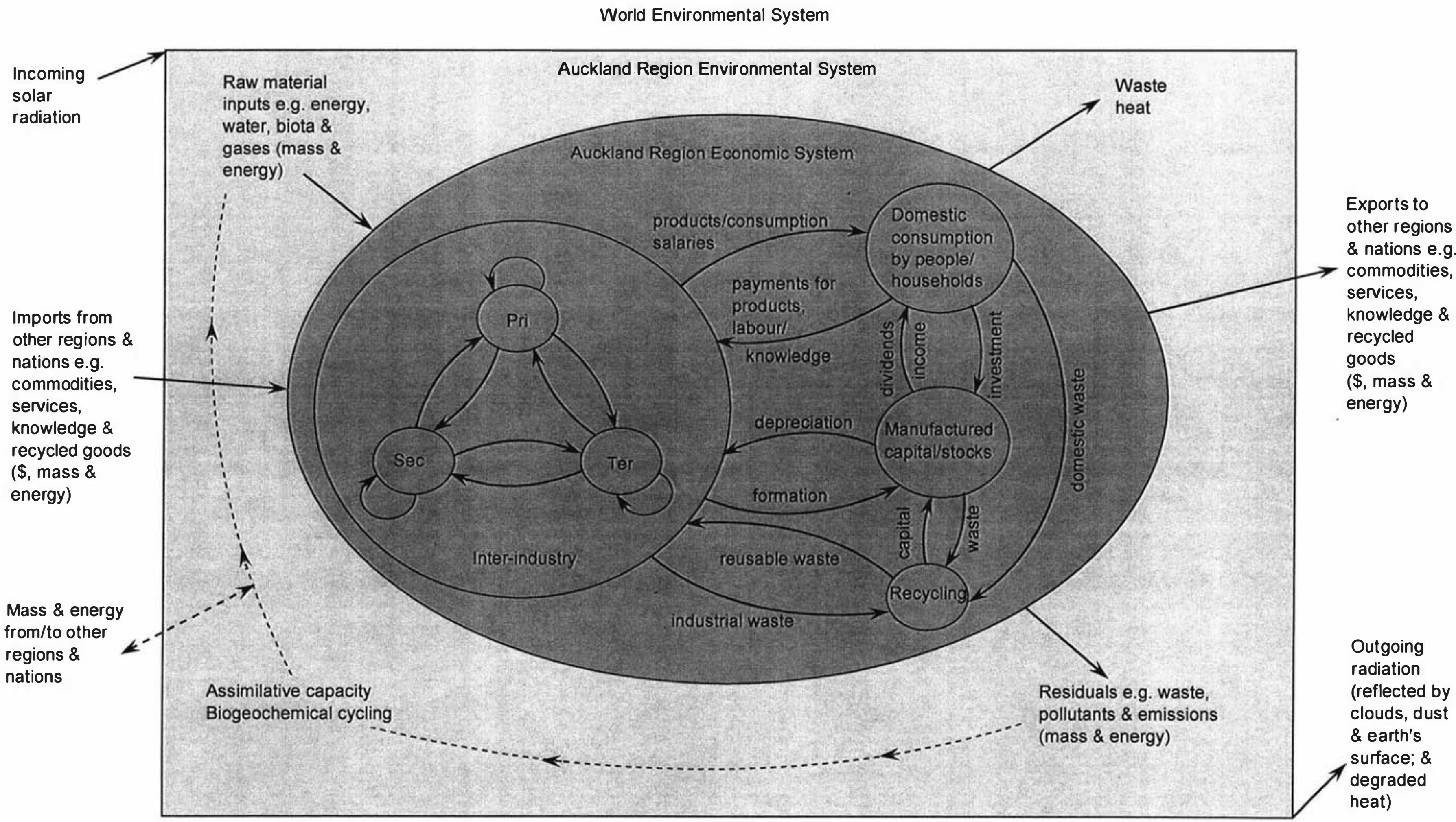

Figure 4.10 Auckland Region's Environment-Economy System with an Expanded Economic System

Daly (1991, p.196) is particular scathing of the above view of an economic system: "Studying an economy in terms of the circular flow without considering the throughput is like studying physiology in terms of the circulatory system without ever mentioning the digestive tract". Greater understanding of the environment-economy system may be obtained by studying Figure 4.10 not only from a conventional economic perspective, but also from a biophysical perspective. The biophysical view of an economic system is as follows. Within an economic system low entropy energy inputs (e.g. fossil fuels) and low entropy matter from the environment (e.g. minerals, biomass, water) are transformed through various production and consumption processes, sometimes stored or recycled, but ultimately degraded into high entropy residuals that flow back into the biophysical environment. A biophysical snapshot of Auckland Region's and New Zealand's within economy flows is generated for the study year using a PIOT in Chapter 6 of this thesis.

Flows across System Interfaces

Figures 4.8 to 4.10 also reveal a number of important economic and biophysical flows that occur between systems. It is beyond the scope of this thesis to model all of these flows – some are modelled, some not at all, some only partially. These flows include (the degree to which they are modelled in this thesis is also indicated):

- *Auckland Region Economic System from/to Auckland Region Environmental System.* This includes the use of raw material inputs (extraction/harvest of natural resources e.g. minerals, energy, soil, water and biota. Inputs from ecosystems e.g. gases for combustion), dumping of residuals (e.g. solid waste, water pollution, gaseous emissions) and release of waste heat. A comprehensive biophysical snapshot of these flows (measured in tonnes) is generated for the study year using a PIOT in Chapter 6 of this thesis.
- *Auckland Region Economic System from/to Other New Zealand Regional Economic Systems.* These flows represent import/exports of economic commodities and services. An interregional trade optimisation model is developed in Chapter 8 and Appendix C that traces import/export flows between Auckland Region and each of New Zealand's fifteen remaining Regional Councils for the study year. The flows in this model are recorded in pecuniary ($), embodied land (ha), and embodied CO_2 (tonne) terms.
- *Auckland Region Economic System from/to the Rest of World Economic System.* These flows represent imports/exports of economic commodities and services. A comprehensive snapshot of these flows (measured in $ and tonnes) is generated for the study year using a financial/physical input-output model in Chapter 5/Chapter 6

respectively of this thesis. Crude estimates of embodied land (ha) and CO_2 (tonne) are also generated for the study year in Chapters 7 and 8 of this thesis.

Other interface flows not involving Auckland Region include:

- *Other New Zealand Regional Economic Systems from/to the Rest of World Economic System.* Financial estimates of these trade flows are generated in Chapter 5 of this thesis for the study year. Estimates of land (ha) and CO_2 (tonnes) embodied in these trade flows are modelled for the study year using the interregional trade optimisation model developed in Chapter 8 and Appendix C of this thesis.
- *Other New Zealand Regional Economic Systems from/to the Rest of New Zealand Environmental System.* This includes the use of raw material inputs, dumping of residuals and release of waste heat. A comprehensive biophysical snapshot of these flows (measured in tonnes) is generated for the study year using a PIOT in Chapter 6 of this thesis.
- *Rest of World Economic System from/to the Rest of World Environmental System.* This includes the use of raw material inputs, dumping of residuals and release of waste heat. These flows are not modelled in this thesis.
- Incoming solar radiation[106] and outgoing radiation[107]. Solar energy is a critical factor in the functioning of many biogeochemical processes – without it life could not exist. Radiation is also lost to space through the reflection by clouds, dust and the Earth's surface, and also as degraded heat. Solar insolation estimates taken directly from scientific literature (Landcare Research, 2003; Patterson, 2005) are used to scale known biogeochemical fluxes at the global level to New Zealand and Auckland Region.

A Note on the Physical Sustainability of the Environment-Economy System:

Using the above conceptualisation, an unsustainable environment-economy system can be thought of as a high waste or throwaway society based on maximising energy and material throughput[108], thereby rapidly converting high quality matter and energy resources into residuals

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[106] Small amounts of radiation are also generated from the Earth's core.
[107] Hydrogen, in its elemental form, may also be lost directly to space.
[108] Kenneth Boulding (1966) first coined the concept of 'throughput'. Boulding advocated that economic systems were embedded within the larger global ecosphere. Moreover, he argued that Earth was a closed thermodynamic system since energy may cross its system boundaries, but not matter. He suggested that by ignoring physical flows at the environment-economy interface, mainstream economics incorrectly thought of the environment as an open system. He draws the analogy of an 'endless frontier' of a 'cowboy economy'. His alternative is a 'spaceship economy' with knowledge, energy and materials used conservatively such that economic throughput remains within Earth's finite bounds. Authors such as Norgaard (1986) and Klaassen and Opschoor (1991) are, however, not so convinced. They argue that

and low quality heat. By contrast, a sustainable environment-economy system would mimic nature by recycling or reusing non-renewable resources, using renewable resources no faster than they are replenished, reducing unnecessary consumption, and minimising residual production. Daly (1973, 1991, 1992) and Goodland and Daly (1993) argue for a 'steady state'[109] economic system based on the thermodynamics laws – ultimately requiring a downscaling in macro-economic activity.

4.4.1.3 Caveats to the Conceptualisation

The above conceptualisation of the environment-economy system has several caveats that require further discussion:

- *Flow quality.* Although the environment-economy framework presented here quantifies many physical and financial flows, it does not however tell us about the quality of these flows. Theorists such as Georgescu-Roegen (1971, 1976), Daly (1977) and Perrings (1987) advocate that it is the entropy law that is the ultimate regulator of all economic activity. Of course, a static accounting framework, such as that developed here, can only provide limited insight into the implications of the entropy law.
- *Aggregation of system entities.* The environment-economy framework presented aggregates across various definitional categories e.g. industries, commodities, raw material inputs, residuals and so on. Of course, this aggregation does not account for, or allude to, the unique characteristics of constituent components. If, for example, insecticides and fertilisers are aggregated to the same industry, there is no accounting for their different risk profiles. Careful classification, or weighting[110] prior to aggregation, is required to minimise the impact of such pitfalls.
- *Temporal boundary.* The financial year ending 31 March 1998 is selected as the accounting period for the environment-economy framework. Unlike financial flows, which are implicitly aligned to financial years, environmental physical flows however tend to correspond to particular events e.g. the impact of a flood event may be understated in the framework as it would be averaged out over the study period. Moreover, many environmental physical flows occur over very large time spans making

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since entropy is a natural process, there is no level below which global entropy will not increase. Instead, they advocate that we must make more efficient use of solar flux to offset or minimise any entropic increase.

[109] Daly (1973, p.98) defines the steady state economy as, "An economy in which the total population and total stock of physical wealth are maintained constant at some desired levels by a minimal rate of maintenance throughput (i.e. by birth and death rates that are equal at the lowest feasible level, and by physical production and consumption rates that are equal at the lowest feasible level)".

[110] Examples of the use of physical weightings include the conversion of greenhouse gases into CO_2 equivalents, and similarly the conversion of halogenated hydrocarbons into CFC-11 equivalents.

their inclusion only largely meaningless e.g. fossil fuels formation. A further complication is that in physical accounting, unlike financial accounting, it is not only the point when commodities are discarded that is important, but also when commodities are acquired. Any comparison between financial and physical matrices will therefore involve some degree of inconsistency.

- *Cause-effect relationships*. The framework neglects the complexity of many cause-effect relationships that exist within the economic and environmental systems. Such relationships are characterised by time lags, non-linearities and feedbacks which, for the most part, cannot be captured in a static system framework. This complexity is considered further in Chapters 10, 11 and Appendix B of this thesis.

4.4.2 Mathematical Description of Auckland Region's Environment-Economy System[111]

4.4.2.1 Economic Input-Output Model

In this Section, a system of supply and use matrices is used to construct an Economic Input-Output Model of commodities flows between industries in the Auckland Region economy. This is a commodity-by-industry input-output accounting framework – identical to the Victor model (Figure 4.6), except it does not include ecological commodities. The model essentially describes flows (in financial terms) in the 'Auckland Region Economic System' ellipse in Figure 4.8.

Structure of the Financial Flow Matrices

A commodity-by-industry model similar to that proposed originally by Stone (1961, 1966), and utilised in analysing environment-economy interactions by Victor (1972a), is adopted here to describe Auckland Region's economic transactions. The matrix structure is compatible with the supply-use framework recommended for national accounting by the United Nations (1999) and followed by Statistics New Zealand (2001g) in compiling the New Zealand Inter-Industry Study 1996. The matrix, depicted in Table 4.1, consists of nine sub-matrices (**R, S, T, U, V, W, X, Y** and **Z**) and five vectors ($\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\delta}$, $\boldsymbol{\varepsilon}$, and $\boldsymbol{\zeta}$).[112] Capital letters are used to denote matrices, while lower case letters are used to denote vectors and scalars. These components are described in detail below.

[111] It is *very* important to note the mathematical notation developed in the remainder of this Chapter is used throughout Chapters 5 and 6, but unless stated otherwise *does not* apply to the remaining Chapters of this thesis.

[112] Although the empty blocks in the Table are devoid of values, they may be derived mathematically under various assumptions.

Table 4.1 Commodity-by-Industry Financial Flow Matrix

		Commodities 1 … Β	Industries 1 … Γ	Final Demands: Household Consumption 1 … Δ	Final Demands: Other Final Demands 1 … Θ	Final Demands: Exports 1 … Λ	Total Use
Commodities 1 … Β			**U** Use	**S** Household Consumption	**T** Other Final Demands	**X** Exports	**α** Gross Commodity Outputs
Industries 1 … Γ		**V** Supply					**β** Gross Industry Outputs
Primary Inputs	Value Added 1 … Π		**W** Value Added	**R** Value Added to Household Consumption	**Z** Value Added to Other Final Demands		**δ** Value Added
Primary Inputs	Imports 1 … Φ	**Y** Imports					
Total Supply		**α'** Gross Commodity Inputs	**β'** Gross Industry Inputs	**ε** Household Consumption	**ζ** Other Final Demand		

Component Matrices and Vectors

Commodity accounts are comprised of matrices **U** ($\mathrm{B} \times \Gamma$), **S**, **T**, **X** and vector **α**. An element $u_{ij} \in \mathbf{U}$ represents, in basic prices, the value of commodity i used by industry j ($i = 1 \ldots \mathrm{B}$; $j = 1 \ldots \Gamma$) within a given financial year. Each column in matrix **U** shows the inputs used by industries classified according to the type of commodity used, while each row shows the inputs of each commodity according to the industries that use it. Matrix **U** is commonly referred to as the 'use', 'industry' or 'absorption' matrix.

Element $s_{ij} \in \mathbf{S}$ represents, in basic prices, the consumption of commodity i by household category j within a given financial year. This includes consumption of consumer durables and non-marketable governmental services[113] by households.

[113] This includes the value of the goods and services provided by the producers of government services for consumption by the community e.g. benefits and pensions, primary and secondary school education, and public health care. A convention is adopted that the government itself is the consumer on behalf of the community.

Element $t_{ij} \in \mathbf{T}$ denotes, in basic prices, the consumption of commodity i by other final demand category j within a given financial year. The following other final demand categories are covered by matrix **T**: gross fixed capital formation and changes in inventories.

Element $x_{ij} \in \mathbf{X}$ denotes, in free on board (fob) terms, the consumption of commodity i by export region j within a given financial year. Depending on their destination, exports are grouped as international (i.e. heading abroad) or interregional (i.e. heading to other New Zealand regions). Together matrices **S**, **T** and **X** represent a complete set of final demand categories.

Element $\alpha_i \in \boldsymbol{\alpha}$ gives the total value of commodity i output as supplied to all industries and final demand categories. Vector $\boldsymbol{\alpha}$ is referred to as 'gross commodity output'. It is calculated by summing the elements of commodity i in matrices **U**, **S**, **T** and **X**. Thus,

$$\alpha_i = \sum_{j=1}^{\Gamma} u_{ij} + \sum_{j=1}^{\Delta} s_{ij} + \sum_{j=1}^{\Theta} t_{ij} + \sum_{j=1}^{\Lambda} x_{ij}\ ,\ \forall\, i, i = 1 \ldots \text{B}. \tag{4.7}$$

Letting **i** denote an appropriately dimensioned column-summing vector, Equation 4.7 may be rewritten as,

$$\mathbf{Ui} + \mathbf{Si} + \mathbf{Ti} + \mathbf{Xi} \equiv \boldsymbol{\alpha}. \tag{4.8}$$

The production relationships within the Auckland Region economy are captured in matrix **V**. An element, $v_{ij} \in \mathbf{V}$, represents, in basic prices, the output of commodity j produced by domestic industry i within a given financial year.[114] In this way, matrix **V** describes the sources of supply of products to the economy. Each row i shows the production of a particular industry classified according to the type of commodity produced, while each column j shows the production of a commodity according to the industries that produced it. This matrix is commonly referred to as the 'supply', 'commodity', 'production' or 'make' matrix.

Element $y_{ij} \in \mathbf{Y}$ denotes, in cost, insurance and freight (cif) terms, imports of commodity j from region i. Depending on their origin, imports are grouped as international (i.e. from abroad) or interregional (i.e. from other New Zealand regions).

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[114] Taxes on products and margins are removed from the Table so that all entries may be expressed in basic prices.

By summing column j of matrices **V** and **Y** the total domestic commodity j output, α_j, may be derived, while summing row i of matrix **V** produces the total domestic industry i output, β_i (know as 'gross industry output'). Hence,

$$\mathbf{i'V} + \mathbf{i'Y} \equiv \boldsymbol{\alpha}' \quad (4.9)$$

and

$$\mathbf{Vi} \equiv \boldsymbol{\beta}. \quad (4.10)$$

Together Equations 4.8 and 4.9 fulfil the first key principle in balancing supply and use tables – the supply of a commodity, α_i, must be equal to the use of that commodity, α'_j, where $i = j$.

The components of value added are recorded in matrix **W**. Value added components include compensation of employees, operating surplus, consumption of fixed capital, taxes on production and subsidies. The element $w_{ij} \in \mathbf{W}$ denotes the value added by component i to the economy in producing column j's industry output within a given financial year. Summing all commodity inputs made to an industry, **i'U**, with the primary inputs made to that same industry, **i'W**, derives an estimate of **β**' (known as 'gross industry input'),

$$\mathbf{i'U} + \mathbf{i'W} \equiv \boldsymbol{\beta}'. \quad (4.11)$$

This fulfils the second key principle in balancing supply and use matrices – that the total output of an industry, β_i, must be equal to its cost of production, β'_j, where $i = j$. Equations 4.7 to 4.11 form the key economic flow accounting identities of the Auckland Region commodity-by-industry model.

Definitions for matrices **R** and **Z**, and the remaining three vectors **σ**, ε and ζ, are however required to complete the economic flow model. Element $r_{ij} \in \mathbf{R}$ represents the expenditure on value added component i by household consumption category j within a given financial year.[115] This includes non-market transfers such as benefits and pensions. Element $z_{ij} \in \mathbf{Z}$ denotes the expenditure on value added component i by final demand category j within a given financial year. Matrix **Z** is a sparsely populated matrix consisting of commodity and non-commodity indirect taxes on products sold directly to capital formation or stored in stocks. Closely associated with matrices **R** and **Z** are vectors **σ**, ε and ζ.

[115] This includes commodities imported by wholesalers/retailers who add a margin and then on-sell to households.

Element $\sigma_i \in \boldsymbol{\sigma}$ represents the total value of value added component i supplied to all industries and final demand categories, thus,

$$\mathbf{Wi} + \mathbf{Ri} + \mathbf{Zi} \equiv \boldsymbol{\sigma}. \qquad (4.12)$$

Element $\varepsilon_j \in \boldsymbol{\varepsilon}$ shows the total expenditure on commodities and value added components by household category j, hence,

$$\mathbf{i'S} + \mathbf{i'R} \equiv \boldsymbol{\varepsilon}. \qquad (4.13)$$

Similarly, element $\zeta_j \in \boldsymbol{\zeta}$ gives the total expenditure on commodities of value added components by other final demand category j, thus,

$$\mathbf{i'T} + \mathbf{i'Z} \equiv \boldsymbol{\zeta}. \qquad (4.14)$$

Gross Domestic Product and Expenditure

An accounting identity equating Gross Domestic Product (GDP) with Gross Domestic Expenditure (GDE) may also be formed from Table 4.1. GDP may be derived by summing the elements of matrices **W**, **R** and **Z**[116], thus,

$$\text{GDP} = \sum\nolimits_{ij} w_{ij} + \sum\nolimits_{ij} r_{ij} + \sum\nolimits_{ij} z_{ij}\,. \qquad (4.15)$$

To derive GDE we must first augment several matrices together. Using | to denote the horizontal augmentation operator, household consumption matrix, **S**, other final demands matrix, **T**, exports matrix, **X**, and a transposed and negated imports matrix, -**Y'**, are augmented together to form a new matrix, $\overline{\mathbf{T}}$. Hence,

$$\overline{\mathbf{T}} = \mathbf{S} \mid \mathbf{T} \mid \mathbf{X} \mid -\mathbf{Y'}. \qquad (4.16)$$

Element $\bar{t}_{ij} \in \overline{\mathbf{T}}$ denotes the value of commodity i sold to final demand category j. In turn, GDE may be derived by summing the elements of matrices $\overline{\mathbf{T}}$, **R** and **Z**, thus,

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[116] Double summations, such as $\sum_{i=1}^{\Pi}\sum_{j=1}^{\Gamma} w_{ij}$, are summarised here as $\sum\nolimits_{ij} w_{ij}$.

$$\text{GDE} = \sum_{ij} \bar{t}_{ij} + \sum_{ij} r_{ij} + \sum_{ij} z_{ij} \, . \tag{4.17}$$

4.4.2.2 Physical Input-Output Model

The Auckland Region economy is inherently dependent on natural resources from the environment and, in turn, on the assimilative capacity of the environment to absorb unwanted by-products. One approach that may be used to capture these dependencies is to measure these flows in physical terms – this, however, is not a trivial task. The United Nations Statistical Commission (2002, p.3-5) has noted that "a complete implementation of [physical] accounts is very ambitious". Physical accounting of the flows identified in Figures 4.8, 4.9 and 4.10 would, at least, require (1) comprehensive accounting, and (2) compliance with fundamental physical laws (i.e. the laws of thermodynamics). It would also be advantageous, from a replication perspective, if the framework made the most of existing accounting practices, definitions, classifications, standards and so on. Additionally, compatibility with the commodity-by-industry financial flow model already developed would permit, to varying degrees, comparisons to be made between physical and financial flow matrices.

Developing a physical accounting framework aligned to Figures 4.8, 4.9 and 4.10 would, however, not be without limitations. It would be difficult, say, for such a framework to capture the key functional relationships of system fluxes characterised by feedback loops, time lags, non-linearities and the like. It is also likely that physical accounting would provide little insight into the qualitative attributes or risk profiles of the flows being measured.[117] Additionally, no assessment is made of 'ecosystem services' which are not only essential for the continuation of life, but also for the enjoyment of life.[118] Nevertheless, despite these limitations, a commodity-by-industry physical flow model is developed here to analyse Auckland Region's environment-economy system.

Structure of the Physical Flow Model

Physical fluxes within the economy, across the environment-economy interface and *vice versa*, are captured by the commodity-by-industry physical flow matrix depicted in Table 4.2. This matrix provides a detailed description of the physical flows within the economy (matrices $\widetilde{\mathbf{U}}$, $\widetilde{\mathbf{S}}$, $\widetilde{\mathbf{T}}$, $\widetilde{\mathbf{V}}$, $\widetilde{\mathbf{X}}$ and $\widetilde{\mathbf{Y}}$), from the environment to either industry for production (matrices $\widetilde{\mathbf{K}}$

[117] Steurer (1996), for example, argues that the toxicity of a physical material is often negatively correlated with its mass.

[118] The importance of ecosystem services to Auckland Region's environment-economy system is investigated further in Chapter 7 and Appendix J.

and $\widetilde{\mathbf{E}}$) or households/capital for final consumption (matrices $\widetilde{\mathbf{H}}$, $\widetilde{\mathbf{G}}$ and $\widetilde{\mathbf{D}}$), and ultimately, from industry or final consumption back to the environment (matrices $\widetilde{\mathbf{Q}}$, $\widetilde{\mathbf{P}}$, $\widetilde{\mathbf{O}}$ and $\widetilde{\mathbf{L}}$). Furthermore, physical flows may also be exchanged with other regions and nations (matrices $\widetilde{\mathbf{X}}$, $\widetilde{\mathbf{Y}}$, $\widetilde{\mathbf{F}}$ and $\widetilde{\mathbf{C}}$ and vector $\widetilde{\boldsymbol{\zeta}}$) or accumulated by households, $\widetilde{\boldsymbol{\pi}}$, in capital, $\widetilde{\boldsymbol{\rho}}$, or within the local environment, $\widetilde{\boldsymbol{\delta}}$ and $\widetilde{\boldsymbol{\psi}}$. Algebraically, the matrix may therefore be described by seventeen sub-matrices and thirteen vectors. The ~ situated above a matrix or vector is used to indicate measurement in physical units (e.g. tonnes).

Table 4.2 Commodity-by-Industry Physical Flow Matrix

	Commodities 1 … B	Industries 1 … Γ	Final Consumption: Household Consumption 1 … Δ	Final Consumption: Capital 1 … Ξ	Final Consumption: Exports 1 … Λ	Raw Material Outputs (Natural Resources and Ecosystem Inputs) 1 … Ψ	Residual Outputs 1 … Ω	Materials Balance	Gross Use
Commodities 1 … B		$\tilde{U}$ Use	$\tilde{S}$ Household Consumption	$\tilde{T}$ Capital Consumption	$\tilde{X}$ Exports				$\tilde{\alpha}$ Commodity Outputs
Industries 1 … Γ	$\tilde{V}$ Supply					$\tilde{Q}$ Raw Materials Generated by Industry	$\tilde{P}$ Residuals Generated by Industry		$\tilde{\beta}$ Industry Outputs
Final Consumption: Household Consumption 1 … Δ							$\tilde{O}$ Residuals Generated by Household Consumption	$\tilde{\pi}$ Net Accumulation by Household Consumption	$\tilde{\varepsilon}$ Household Consumption Outputs
Final Consumption: Capital 1 … Ξ							$\tilde{L}$ Residuals Generated by Capital Consumption	$\tilde{\rho}$ Net Accumulation by Capital Consumption	$\tilde{\eta}$ Capital Consumption Outputs
Final Consumption: Imports 1 … Φ	$\tilde{Y}$ Imports							$\tilde{\varsigma}$ Net Accumulation by Imports	$\tilde{\theta}$ Imports
Raw Materials Inputs (Natural Resources and Ecosystem Inputs) 1 … Ψ		$\tilde{K}$ Raw Materials to Industry	$\tilde{H}$ Raw Materials to Household Consumption	$\tilde{G}$ Raw Materials to Capital Consumption	$\tilde{F}$ Raw Materials Exported	*Biogeochemical Cycling Model* (included for conceptual completeness, but not included in the Chapter 6 physical input-output model)		$\tilde{\sigma}$ Net Accumulation of Raw Materials	$\tilde{\lambda}$ Material Inputs
Residual Inputs 1 … Ω		$\tilde{E}$ Residuals to Industry		$\tilde{D}$ Residuals to Capital Consumption	$\tilde{C}$ Residuals Exported			$\tilde{\varphi}$ Net Accumulation of Residuals	$\tilde{\mu}$ Residual Inputs
Gross Supply	$\tilde{\alpha}'$ Commodity Inputs	$\tilde{\beta}'$ Industry Inputs	$\tilde{\varepsilon}'$ Household Consumption Inputs	$\tilde{\eta}'$ Capital Consumption Inputs	$\tilde{\xi}$ Exports	$\tilde{\lambda}'$ Material Outputs	$\tilde{\mu}'$ Residual Outputs		

Component Matrices and Vectors

Matrices $\widetilde{\mathbf{U}}$, $\widetilde{\mathbf{S}}$, $\widetilde{\mathbf{T}}$, $\widetilde{\mathbf{X}}$, $\widetilde{\mathbf{V}}$ and $\widetilde{\mathbf{Y}}$ are physical equivalents (measured in tonnes) of their financial counterparts described in Table 4.1. An element $\widetilde{u}_{ij} \in \widetilde{\mathbf{U}}$ therefore represents the physical quantity of commodity i used by industry j (i = 1 … Β; j = 1 … Γ) within a given financial year. Each column in matrix $\widetilde{\mathbf{U}}$ shows the physical inputs used by industries classified according to the type of commodity used, while each row shows the inputs of each commodity according to the industries that use it. Apart from the inclusion of matrices catering for raw material inputs/outputs and residual inputs/outputs, Table 4.2 incorporates two subtle, but important changes from Table 4.1: (1) the value added matrices **W**, **R** and **Z** are omitted as they have no associated physical flows, and (2) household consumption and capital formation are mirrored on both axes.

The environmental input-output matrices in the bottom left and top right hand corners may be read in an analogous manner to the following example. Row entries in the household consumption row matrix, $\widetilde{\mathbf{O}}$, describe the origin of residual outputs from household consumption (i.e. household consumption category i is the origin of residual j), while column entries in the household consumption column matrix, $\widetilde{\mathbf{H}}$, denote the destination of raw materials to household consumption (i.e. household consumption category j is the destination of raw material i). In other words, the environmental input matrices (bottom left) describe the inputs of raw materials and residuals used by household consumption, capital formation and exports, while the environmental output matrices (top right) describe the raw material and residual outputs generated by industries, household consumption, capital formation and imports.

The matrix for manufactured commodities comprise sub-matrices $\widetilde{\mathbf{U}}$, $\widetilde{\mathbf{S}}$, $\widetilde{\mathbf{T}}$ and $\widetilde{\mathbf{X}}$ and vector $\widetilde{\boldsymbol{\alpha}}$.[119] In a similar manner to Equation 4.8, the vector $\widetilde{\boldsymbol{\alpha}}$ may be defined as,

$$\widetilde{\mathbf{U}}\mathbf{i} + \widetilde{\mathbf{S}}\mathbf{i} + \widetilde{\mathbf{T}}\mathbf{i} + \widetilde{\mathbf{X}}\mathbf{i} \equiv \widetilde{\boldsymbol{\alpha}}, \tag{4.18}$$

while the production relationships are captured in physical terms in the regional supply, $\widetilde{\mathbf{V}}$, and imports, $\widetilde{\mathbf{Y}}$, matrices. By summing the columns of $\widetilde{\mathbf{V}}$ and $\widetilde{\mathbf{Y}}$, the gross physical mass of commodity j output, $\widetilde{\alpha}'_j$, may be derived, thus,

[119] To establish mass balance identities between the economic and environmental flow matrices requires that all transactions be expressed in mass terms. For all earthly purposes mass and weight may be considered to be equivalent.

$$\mathbf{i'}\widetilde{\mathbf{V}} + \mathbf{i'}\widetilde{\mathbf{Y}} \equiv \widetilde{\boldsymbol{\alpha}}'. \tag{4.19}$$

Together Equations 4.18 and 4.19 formulate the first key principle in balancing the physical supply and use matrices – the physical supply of a commodity, $\widetilde{\alpha}_i$, must be equal to the use of that commodity, $\widetilde{\alpha}'_j$, where $i = j$.

Summing row i of matrices $\widetilde{\mathbf{V}}$, $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{P}}$ defines the gross physical mass of domestic industry i output, $\widetilde{\beta}_i$, thus,

$$\widetilde{\mathbf{V}}\mathbf{i} + \widetilde{\mathbf{Q}}\mathbf{i} + \widetilde{\mathbf{P}}\mathbf{i} = \widetilde{\boldsymbol{\beta}}. \tag{4.20}$$

An element $\widetilde{q}_{ij} \in \widetilde{\mathbf{Q}}$ represents the physical output of raw material j generated by industry i within a given financial year. This is a sparsely populated matrix made up of livestock, trees and some plant species. Similarly, element $\widetilde{p}_{ij} \in \widetilde{\mathbf{P}}$ denotes the physical output of residual j generated by industry i within a given financial year. Unlike matrix $\widetilde{\mathbf{Q}}$, matrix $\widetilde{\mathbf{P}}$ is a densely populated matrix capturing the solid wastes, air emissions and water pollutants generated by industry.

Industries, like commodities, must be in materials balance. Thus,

$$\mathbf{i'}\widetilde{\mathbf{U}} + \mathbf{i'}\widetilde{\mathbf{K}} + \mathbf{i'}\widetilde{\mathbf{E}} \equiv \widetilde{\boldsymbol{\beta}}', \tag{4.21}$$

where an element $\widetilde{k}_{ij} \in \widetilde{\mathbf{K}}$ denotes raw material input i into industry j. Matrix $\widetilde{\mathbf{K}}$ includes natural resource inputs and ecosystem inputs. Similarly, element $\widetilde{e}_{ij} \in \widetilde{\mathbf{E}}$ represents residual input i into industry j. Matrix $\widetilde{\mathbf{E}}$ is a sparsely populated matrix including economic residuals recycled from nature by industry. Taken together, Equations 4.20 and 4.21 fulfil the second key principle of materials balance in the commodity-by-industry physical flow matrix – gross physical industry output, $\widetilde{\beta}_i$, must equal gross physical industry input, $\widetilde{\beta}'_j$, where $i = j$. Equations 4.18 to 4.21 form the key physical flow identities associated with economic production.

The remaining matrices of Table 4.2 focus on fluxes between the environment and final consumption (i.e. the use of raw materials and residuals by final consumption and as denoted by matrices $\widetilde{\mathbf{H}}$, $\widetilde{\mathbf{G}}$, $\widetilde{\mathbf{F}}$, $\widetilde{\mathbf{D}}$ and $\widetilde{\mathbf{C}}$), conversely, fluxes between final demand and the environment (i.e. the generation of raw materials and residuals by final consumption as denoted by matrices $\widetilde{\mathbf{O}}$ and $\widetilde{\mathbf{L}}$), and various materials balance vectors ($\widetilde{\boldsymbol{\pi}}$, $\widetilde{\boldsymbol{\rho}}$, $\widetilde{\boldsymbol{\varsigma}}$, $\widetilde{\boldsymbol{\sigma}}$ and $\widetilde{\boldsymbol{\varphi}}$).

Element $\widetilde{h}_{ij} \in \widetilde{\mathbf{H}}$ denotes the raw material input *i* into household consumption category *j*. This includes, for example, household extraction of water for domestic supply, oxygen for combustion in private motor vehicles, and the private harvesting of vegetables and fruits and so on. Summing the columns of matrices $\widetilde{\mathbf{S}}$ and $\widetilde{\mathbf{H}}$ gives gross physical household consumption of inputs, $\widetilde{\boldsymbol{\varepsilon}}'$,

$$\mathbf{i}'\widetilde{\mathbf{S}} + \mathbf{i}'\widetilde{\mathbf{H}} \equiv \widetilde{\boldsymbol{\varepsilon}}' , \qquad (4.22)$$

while summing the rows of matrix $\widetilde{\mathbf{O}}$, household residuals produced, and vector $\widetilde{\boldsymbol{\pi}}$, net accumulation of household durables, a mass balance may be established for household consumption, $\widetilde{\boldsymbol{\varepsilon}}$,

$$\widetilde{\mathbf{O}}\mathbf{i} + \widetilde{\boldsymbol{\pi}} \equiv \widetilde{\boldsymbol{\varepsilon}} , \qquad (4.23)$$

where element $\widetilde{o}_{ij} \in \widetilde{\mathbf{O}}$ denotes residual *j* generated by household consumption category *i*, and element $\widetilde{\pi}_i \in \widetilde{\boldsymbol{\pi}}$ represents net accumulation of durables by household consumption category *i*. Matrix $\widetilde{\mathbf{O}}$ includes residuals, pollutants and the like discharged directly by households into the environment, while vector $\widetilde{\boldsymbol{\pi}}$ comprises the accumulation of consumer durables (manufactured commodities) by households.

Similarly, a mass balance may also be defined for capital formation by summing the columns of matrices $\widetilde{\mathbf{T}}$, $\widetilde{\mathbf{G}}$ and $\widetilde{\mathbf{D}}$,

$$\mathbf{i}'\widetilde{\mathbf{T}} + \mathbf{i}'\widetilde{\mathbf{G}} + \mathbf{i}'\widetilde{\mathbf{D}} \equiv \widetilde{\boldsymbol{\eta}}' , \qquad (4.24)$$

where element $\tilde{g}_{ij} \in \tilde{\mathbf{G}}$ denotes raw material i used in forming capital category j, element $\tilde{d}_{ij} \in \tilde{\mathbf{D}}$ represents residual input i used in forming capital category j, and $\tilde{\eta}'_j \in \tilde{\boldsymbol{\eta}}'$ gives gross physical inputs into capital formation. Matrix $\tilde{\mathbf{D}}$ consists of, for example, recycled or reused solid waste from controlled landfills. Accordingly, summing the rows of matrix $\tilde{\mathbf{L}}$, residuals generated in forming capital, and vector $\tilde{\boldsymbol{\rho}}$, net accumulation of manufactured capital, establishes a mass balance for capital formation,

$$\tilde{\mathbf{L}}\mathbf{i} + \tilde{\boldsymbol{\rho}} \equiv \tilde{\boldsymbol{\eta}}, \qquad (4.25)$$

with $\tilde{l}_{ij} \in \tilde{\mathbf{L}}$ denoting residual j produced by capital formation category i, and $\tilde{\rho}_i \in \tilde{\boldsymbol{\rho}}$ the net accumulation of manufactured capital category i.

Empirically, vectors $\tilde{\boldsymbol{\pi}}'$ and $\tilde{\boldsymbol{\rho}}'$ may be algebraically formulated; for example, $\tilde{\boldsymbol{\pi}}'$ is found by summing the rows of matrix $\tilde{\mathbf{O}}$, transposing the result, and subtracting this from vector $\tilde{\boldsymbol{\varepsilon}}'$, thus,

$$\tilde{\boldsymbol{\pi}}' = \tilde{\boldsymbol{\varepsilon}}' - \tilde{\mathbf{O}}\mathbf{i}' \ . \qquad (4.26)$$

Over and above the economic trade physical flows, captured in matrices $\tilde{\mathbf{X}}$ and $\tilde{\mathbf{Y}}$, raw materials and residuals (e.g. recycled commodities) may also be exchanged with other regions and nations. While non-economic flows may be captured in detail by separating domestic flows from those originating from, or destined to, other regions and nations[120], the approach taken here is simply to attribute these flows to matrices $\tilde{\mathbf{F}}$ and $\tilde{\mathbf{C}}$.[121] Element $\tilde{f}_{ij} \in \tilde{\mathbf{F}}$ denotes the export of raw material i to export region j, and similarly, element $\tilde{c}_{ij} \in \tilde{\mathbf{C}}$ represents the export of residual i to export region j. Matrix $\tilde{\mathbf{F}}$ is a sparsely populated matrix capturing, for example, fish resources harvested by foreign regions and nations. Matrix $\tilde{\mathbf{C}}$ includes oxygen and water taken by ocean-going vessels from other regions and nations.

[120] For example, matrix $\tilde{\mathbf{K}}$ could be separated into two sub-matrices, the first representing the utilisation of domestic raw materials, and the second traded raw materials.
[121] The implications of tourist activity are particularly difficult to demarcate. Carbon dioxide emissions from international air travel, for example, could be coded in several ways – each resulting in inclusion in a different matrix in Table 4.2 e.g. to the region of origin, to the region of destination, or on a pro-rata basis weighted by distance within a region's airspace and so on.

The gross export of physical mass, $\widetilde{\zeta}$, may be defined by summing the columns of matrices $\widetilde{\mathbf{X}}$, $\widetilde{\mathbf{F}}$ and $\widetilde{\mathbf{C}}$, thus,

$$\mathbf{i}'\widetilde{\mathbf{X}} + \mathbf{i}'\widetilde{\mathbf{F}} + \mathbf{i}'\widetilde{\mathbf{C}} \equiv \widetilde{\zeta}', \qquad (4.27)$$

and a physical balance of trade by subtracting a transposed row summation of matrix $\widetilde{\mathbf{Y}}$, hence,

$$\widetilde{\varsigma}' = \widetilde{\zeta} - \mathbf{i}'\widetilde{\mathbf{Y}}. \qquad (4.28)$$

If $\widetilde{\varsigma}$ is positive then the region has a net physical trade surplus, else the region has a net physical trade deficit. Hence, the vector $\widetilde{\boldsymbol{\theta}}$ may be determined as the sum of the row entries in matrix $\widetilde{\mathbf{Y}}$ and vector $\widetilde{\varsigma}$, therefore

$$\widetilde{\boldsymbol{\theta}} \equiv \widetilde{\mathbf{Y}}\mathbf{i} + \widetilde{\varsigma}, \qquad (4.29)$$

where $\widetilde{\theta}_i \in \widetilde{\boldsymbol{\theta}}$ denotes gross physical imports by import category *i*.

The final materials balance equations that may be established in Table 4.2 relate to the accumulation of raw materials and residuals within the environment. Summing the column entries of matrix $\widetilde{\mathbf{Q}}$ gives $\widetilde{\boldsymbol{\lambda}}'$, and subtracting a transposed summation of matrices $\widetilde{\mathbf{K}}$, $\widetilde{\mathbf{H}}$, $\widetilde{\mathbf{G}}$ and $\widetilde{\mathbf{F}}$ provides an estimate of $\widetilde{\boldsymbol{\sigma}}$, the net accumulation of raw materials within the environment,

$$\widetilde{\boldsymbol{\sigma}} = \widetilde{\boldsymbol{\lambda}}' - (\widetilde{\mathbf{K}}\mathbf{i} + \widetilde{\mathbf{H}}\mathbf{i} + \widetilde{\mathbf{G}}\mathbf{i} + \widetilde{\mathbf{F}}\mathbf{i})'. \qquad (4.30)$$

Similarly, summing the column entries of matrices $\widetilde{\mathbf{P}}$, $\widetilde{\mathbf{O}}$ and $\widetilde{\mathbf{L}}$ gives $\widetilde{\boldsymbol{\mu}}'$ and, in turn, subtracting a transposed summation of matrices $\widetilde{\mathbf{E}}$, $\widetilde{\mathbf{D}}$ and $\widetilde{\mathbf{C}}$ gives $\widetilde{\boldsymbol{\varphi}}$, the net accumulation of residuals within the environment,

$$\widetilde{\boldsymbol{\varphi}} = \widetilde{\boldsymbol{\eta}}' - (\widetilde{\mathbf{E}}\mathbf{i} + \widetilde{\mathbf{D}}\mathbf{i} + \widetilde{\mathbf{C}}\mathbf{i})'. \qquad (4.31)$$

Finally, the conversion of residuals outputs to raw material inputs, irrespective of whether they are produced within the economy or environment, takes place through various biogeochemical cycles. Phosphorus leached from soils may, via runoff and river transportation, find its way into the sea. Over time it is possible, through the processes of sedimentation, sedimentary rock formation and tectonic uplift, that the phosphorus may once again exist within soil – thereby completing the cycle. These transformations are encapsulated in the block labelled 'Biogeochemical Cycling Model'. Since they occur over time periods both much shorter, or typically much longer, than a financial year and also tend to be dynamic and non-linear rather than static, their inclusion in the accounting framework is considered inappropriate. Instead, they are modelled separately in Chapter 7 and Appendix B.

A Note on Spatial Location

If the spatial location of the raw materials utilised (or generated) by the economy, or alternatively, the residuals generated (or utilised) by the economy, are to be captured in the framework, then Table 4.2 requires modification. Since environmental problems are often spatially explicit, particularly air and water pollution, the identification of, say, ecologically sensitive areas, water catchments, densely populated localities or the like within Auckland Region would undoubtedly improve the framework's usefulness. Spatial disaggregation of the matrices in Table 4.2 may be achieved either by assigning each raw material/residual type a spatial location, or by assigning each spatial location a complete set of raw material/residual types. As both approaches are simply rearrangements of equivalent information, the selection of one approach over the other is only a matter of presentation.

4.4.3 Conversion to an Inter-Industry Framework

The commodity-by-industry accounting framework described in Section 4.4.2.1 has the advantage of being able to account for multiple outputs per industry, rather than assuming there is one homogeneous output. However, for the purposes of multiplier analysis (refer to Chapters 5, 6, 7 and 8, and Appendix G), using commodity-by-industry models are often problematic as:

- *Analytical ease of use*. Commodity-by-industry models are often rectangular matrices which means that straightforward matrix algebra (based on square matrices) cannot be used; and
- *Negative coefficients*. Commodity-by-industry models usually have multiple outputs per industry, which inevitably generates negative coefficients. As others (e.g. Almon,

2000) have pointed out these negative coefficients are problematic as they make no economic sense.

In order, therefore, that the derivation of economic multipliers (Chapter 5, Appendix G), ecological multipliers (Chapter 6, Chapter 7) and ecological footprints (Chapter 8) could be successfully undertaken, the procedure described below which converts a commodity-by-industry economic model (outlined in Section 4.4.2.1) into an industry-by-industry economic model was used.

4.4.3.1 Commodity Technology and Industry Technology Assumptions

Under ideal circumstances an inter-industry matrix would be derived from source data describing the input structure of every type of activity producing a single commodity. This ensures homogeneity except in those cases where secondary products (i.e. by-products and joint products) are intrinsic to the production process, e.g. it is physically impossible to separate meat (main product) and offal (by-product) production. Most statistical agencies, however, can only derive inter-industry matrices according to enterprise definitions which, in turn, may be complicated with many secondary products. To minimise the bias resulting from the presence of joint/by-products, statistical agencies carefully craft business census questionnaires to utilise itemised cost accounting definitions which aid in separating secondary products. Alternatively, input-output compilers may utilise, in combination with census questionnaires, approaches such as the 'redefinition method', 'negative transfer method', 'aggregation' or 'positive transfer method' to deal with secondary products (United Nations, 1999). Data availability, confidentiality, cost/time constraints and so on all prohibit the use of such procedures in this thesis.

Crude inter-industry matrices may however be generated mechanically by assuming one of two possible production pathways: commodity-based or industry-based technology.[122] Under the commodity technology assumption industries produce commodities in fixed proportions (Jackson, 1998; United Nations, 1999). A given commodity therefore has the same input structure irrespective of the industry that produces it. By contrast, under the industry technology assumption, inputs are consumed in the same fixed proportions independently of the commodity being produced by an industry (Jackson, 1998; United Nations, 1999). Primary and secondary products are therefore assumed to be produced using the same technology.

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[122] Recently Konijn and Steenge (1995) have proposed, and convincingly argued for, the use of an activity-based technology assumption.

Various input-output analysts have critiqued each assumption's pros and cons – for example, refer to ten Raa *et al.* (1984), Kop Jansen and ten Raa (1990), Konijn and Steenge (1995) and the United Nations (1999). Kop Jansen and ten Raa (1990, p.214) argue that selection of one assumption over another is simply a "matter of judgement or taste". The United Nations (1999) provides strong theoretical justifications for the adoption of a commodity technology assumption[123], but acknowledges that due to the presence of joint/by-products negative coefficients may be produced in multiplier calculations[124], or when key balance identities are not adhered to. Given that the industry technology assumption guarantees positive inter-industry coefficients and has been widely utilised[125], it is selected here as the approach for generating inter-industry matrices.

4.4.3.2 Generating an Inter-Industry Matrix Using the Industry Technology Assumption

Under an industry technology assumption, the relationship between commodity input and industry output, in matrix **V**, provides the basis for a transformation from commodity to industry space.[126] Such a transformation, and the subsequent generation of an inter-industry matrix, requires several steps.

Step I Estimate Gross Commodity Outputs Required for Domestic Purposes

We begin by estimating gross commodity outputs required for domestic purposes, $\bar{\boldsymbol{\alpha}}$, as

$$\bar{\boldsymbol{\alpha}}=\boldsymbol{\alpha}-(\mathbf{i}'\mathbf{Y})', \tag{4.32}$$

where **i** denotes an appropriately dimensioned column-summing vector.

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[123] The United Nations (1999) argues that the industry technology assumption is "economically nonsensical" (p.99) as commodities are produced with the same input structures irrespective of the industry they are produced in. If two commodities have the same costs, because they are produced by the same technology (i.e. in a perfectly competitive market where prices equal costs), it then follows that they cannot have different prices. But this is what is required by the industry technology assumption. Furthermore, this assumption requires that market shares remain constant over time – which is also implausible.

[124] The United Nations (1999) puts forward a suite of *ad hoc* methods for dealing with negative coefficients. Almon (2000) has also proposed a methodology for generating non-negative multipliers under the commodity technology assumption.

[125] The United Nations (1968) SNA handbook advocated the adoption of an industry technology assumption in constructing inter-industry accounts.

[126] By corollary, the inverse of **F** may be used to transform a matrix from industry to commodity space.

Step 2 Calculate Domestic Industry Production of Commodities for Export

This requires construction of a matrix of commodity-by-industry direct requirements coefficients, **B**, by defining a fixed relationship between commodity input and industry output values. Thus,

$$\mathbf{B} = \mathbf{V}\,\hat{\boldsymbol{\alpha}}^{-1}, \tag{4.33}$$

followed by estimation of a column vector, **Xi**, of total exports,

$$\gamma = \mathbf{Xi}\,. \tag{4.34}$$

Diagonalising γ and then premultiplying it by **B** yields domestic production of commodities for export,

$$\mathbf{M} = \mathbf{B}\hat{\gamma}\,. \tag{4.35}$$

Step 3 Calculate Total Supply for Domestic Use

Subtracting **M** from **V** gives the domestic supply by industry, and augmenting this with a row for imports gives total supply for domestic use,

$$\mathbf{N} = \begin{pmatrix} \mathbf{V} - \mathbf{M} \\ \mathbf{i'Y} \end{pmatrix}. \tag{4.36}$$

The values of matrix **N** represent the commodities, domestically produced and imported, that are required to support intermediate demand and final domestic demand. Standardising **N** yields a matrix, $\dddot{\mathbf{N}}$, that shows the composition of industry and import sources of commodity production for domestic demand with columns summing to one.[127]

[127] A $\dddot{}$ is placed above matrix **N** to indicate that it has been standardised. Mathematically, standardisation is achieved by the following formula: $\mathbf{N}\widehat{(\mathbf{i'N})}^{-1}$.

Step 4 Transform U | T from Commodity to Industry Space

Postmultiplying $\dddot{\mathbf{N}}$ by **U | T** completes the transformation to industry space. Matrices **W, R** and **Z** may then be inserted – no mathematical manipulation of these matrices is required as they are already in the required form. In this way, the entire inter-industry framework may be generated,

$$\left(\begin{array}{cc|c} \dddot{\mathbf{N}}\mathbf{U} & \dddot{\mathbf{N}}\mathbf{T} & \begin{array}{c}\mathbf{B}\gamma \\ \hline \mathbf{0}\end{array} \\ \hline \multicolumn{2}{c|}{\mathbf{W}\,\mathbf{R}\,\mathbf{Z}} & \end{array}\right). \tag{4.37}$$

Chapter Five

Economic Input-Output Model: Financial Flows in the Auckland Region Economy

In Chapter 5 an economic input-output model of the Auckland Region economy is constructed, using the commodity-by-industry framework (Table 4.1) mathematically defined in Chapter 4. The reasons for constructing this economic input-output model of the Auckland Region economy are several:

- *Structural relationships.* To understand the issues concerning the sustainability and growth of the Auckland Region, it is essential to appreciate the *structural relationships* in the Auckland Region economy, as the economy is arguably the 'engine room' and 'driver' of human activity in the Region. These structural relationships are conventionally analysed by using an economic input-output model such as the one developed in this Chapter;
- *Basis for physical input-output model.* The economic input-output model is a starting point for constructing the physical input-output model which is in turn required to gain an appreciation of the biophysical (urban metabolism) aspects of the sustainability of the Auckland Region; and
- *Basis for ecological footprinting.* In this thesis, the economic input-output model, along with a multi-regional economic input-output model, is the core analytical tool used to calculate the ecological footprint of the Auckland Region – i.e. how, in structural terms, does Auckland Region *ecologically* depend on other regions and, for that matter, other countries?
- *Basis for dynamic modelling.* The *static* economic input-output model developed in this Chapter is the starting point for constructing the *dynamic* input-output model in Chapter 11 of this thesis;

A commodity-by-industry economic input-output model is constructed for Auckland Region as the preferred framework, as it allows for multiple outputs per industry, thereby providing for a more realistic representation of the economy. This is particularly important in the construction of the physical input-output model, where the aggregation of all outputs into one homogeneous industry output becomes particularly troublesome. The regionalisation of commodity-by-industry models has, however, only been described in the literature only recently (Jackson, 1998 and Lahr, 2001) with no reported actual operationalisation of such methods. This thesis proposes and then operationalises such a commodity-by-industry regionalisation method so that an Auckland Region model can be constructed from the New Zealand model, drawing on and extending the methods of Jackson (1998) and Lahr (2001).

5.1 Generation of the Auckland Region Economic Input-Output Model

5.1.1 Previous Regional-Level Economic Input-Output Models

Since the 1970s input-output analysis has been the method of choice for analysing regional economic activity. Consequently, there has been a great deal of interest in methods for constructing regional economic input-output models (for reviews, see Round (1983), Miller and Blair (1985), Hewings and Jensen (1986) and Jensen (1990)). Most of this work has focused on methods for deriving regional inter-industry models from national equivalents.[128] However, this traditional focus on industries has been questioned on theoretical grounds (Madsen and Jensen-Butler, 1998, 1999) as neglecting the key attributes of the regional commodity-by-industry (functional) accounting framework. Apart from the analytical advantages of the commodity-by-industry model, it is a more reasonable form for data collection and handles secondary or joint products more effectively (St Louis, 1989). It is not only capable of answering the same questions as the inter-industry or Leontief format, albeit with mathematical transformation, but also others that the latter cannot. A researcher may, for example, construct commodity-by-commodity, commodity-by-industry, industry-by-commodity or inter-industry models depending on the research interest. Furthermore, as Oosterhaven (1984) points out, it is particularly useful for interregional or multi-regional models where trade flows are typically in terms of commodities rather than industries.

The statistical agencies of several nations, including the Netherlands, Finland, Denmark and Canada, have created regional level commodity-by-industry accounting frameworks using surveys e.g. Oosterhaven (1984), Boomsma and Oosterhaven (1992), Siddiqi and Salem (1995), Eding and Oosterhaven (1996), Eding *et al.* (1998), Piispala (1998, 2000) and Madsen and Jensen-Butler (1998, 1999). Between late 2002 and mid 2003 Statistics New Zealand (SNZ) investigated the possibility of developing survey-based regional input-output models in New Zealand. This feasibility study assessed user requirements, reviewed existing New Zealand and

[128] Jackson (1998) attributes this focus to several factors including inertia, industry-based statistical reporting by government agencies, and because economic impact assessment, arguably the most common application of input-output analysis, requires only inter-industry matrices. Regional inter-industry tables have been developed in New Zealand by Hubbard and Brown (1981), Moore (1981), Butcher (1985), Kerr, Sharp and Gough (1986) and McDonald (1997, 1999a).

international methodologies[129], evaluated data sources and provided recommendation for a development plan (Statistics New Zealand, 2002, 2003a, 2003b, 2003c). It was concluded that if official regional input-output tables were to be developed that these would adopt the national commodity-by-industry framework, however, "limited data availability restricts any official development" (Statistics New Zealand, 2003a, p.8).

When time and cost constraints prohibit the development of survey-based regional tables, as is the case here, input-output practitioners have typically turned to 'non-survey' methodologies that mechanically reduce national coefficients to regional equivalents. Czamanski and Malizia (1969), Schaffer and Chu (1969, 1971) and Smith and Morrison (1974), compared survey-based industry-by-industry matrices and synthetic equivalents produced by the most commonly used non-survey techniques (refer to Appendix D for a review of these methods). Although non-survey coefficients were consistently larger than their survey counterparts, the Simple Location Quotient (SLQ) method and $\mathbf{R\hat{A}S}$ constrained matrix technique generated reasonable estimates (refer to Appendix D for further explanation). Despite the considerable research effort directed at industry-by-industry matrix regionalisation using non-survey methodologies, literature on the regionalisation of commodity-by-industry matrices using non-survey methods remains scarce – notable exceptions include Jackson (1998) and Lahr (2001). Statistics New Zealand's (2003a, p.8) feasibility study concluded that the development of regional input-output tables "would begin with a simple non-survey-based methodology and move toward more complex survey-based methods over time".

5.1.2 Methodological Process Used in the Auckland Region Study

In Sections 5.1.3 and 5.1.4, a non-survey method is developed that generates a regional commodity-by-industry model for Auckland Region through a series of 11 mechanical steps using a modicum of Auckland Region-specific data (Figure 5.1). Section 5.1.3 (steps 1 to 4) updates the national use and supply matrices from 1996 to 1998 for volume, price and productivity changes, while Section 5.1.4 (steps 5 to 11) regionalises the updated New Zealand commodity-by-industry model using the SLQ technique. This technique has successfully been applied to inter-industry regionalisation in New Zealand by analysts such as Hubbard and Brown (1981), Butcher (1985), Kerr *et al.* (1986), McDonald and Patterson (1994, 1995a, 1995b, 1995c), Patterson and McDonald (1996), Ministry of Agriculture and Forestry (1997) and McDonald (1999a). A key feature of the regionalisation procedure is that it provides significant opportunities for the insertion of superior data. Figure 5.1 provides an overview of

[129] This included a review of the three most widely utilised regionalisation methodologies within New Zealand, including one developed by the author.

the methodological steps undertaken in the generation of the Auckland Region Economic Input-Output Model (commodity-by-industry).

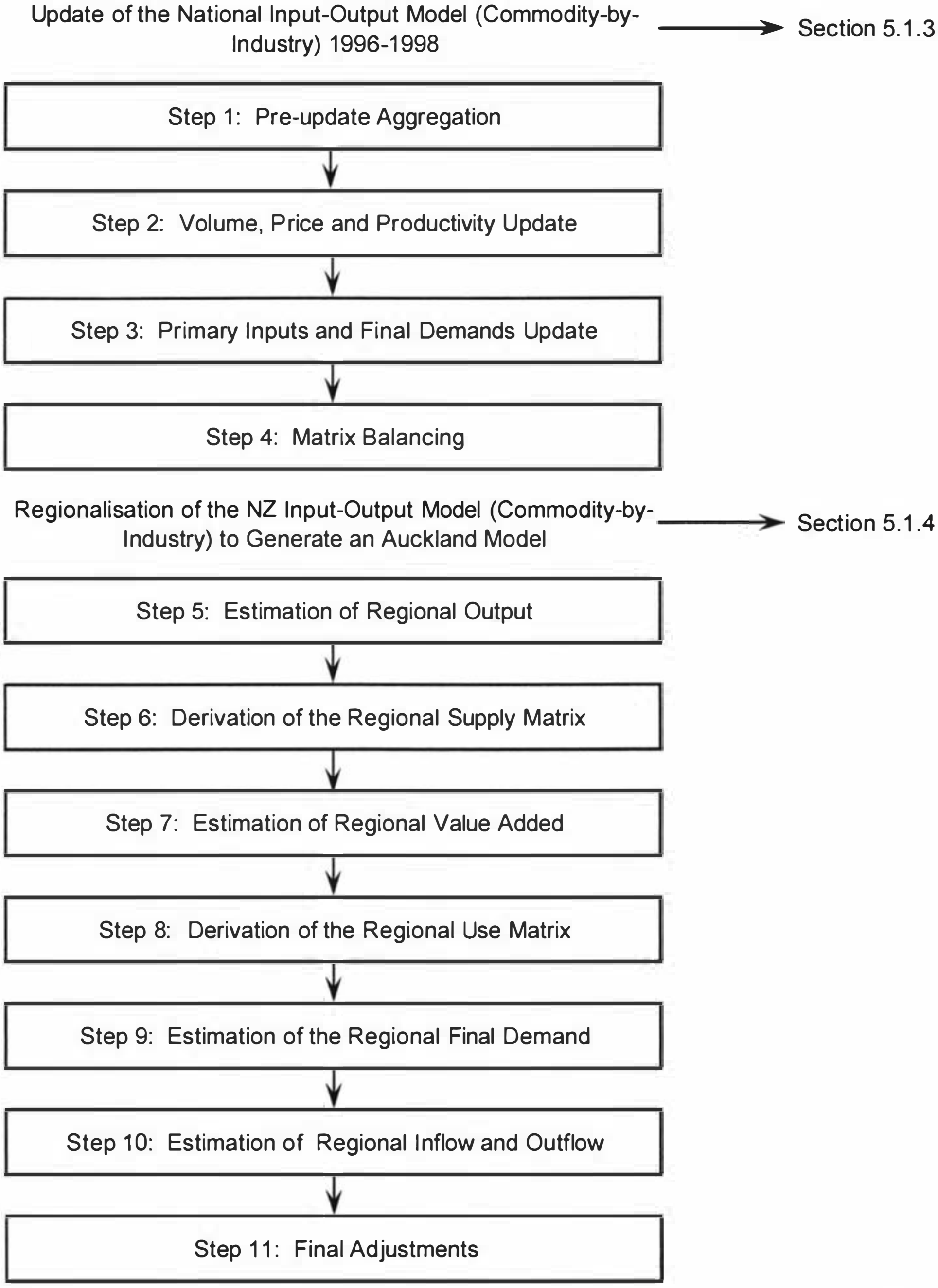

Figure 5.1 Methodological Process for Generating an Auckland Region Economic (Commodity-by-Industry) Input-Output Model

The following statistical data sources were employed in the construction of the commodity-by-industry model for the Auckland Region economy:

- 1996 Inter-industry Study of the New Zealand Economy (Statistics New Zealand, 2001g).

- 1996, 1998 and 2001 full time equivalent (FTE) employment at the five-digit level as extracted from the Business Directory (Statistics New Zealand, 1996b, 1998c, 2001b)
- 1998 Labour Force Survey FTE Employment (Statistics New Zealand, 1998g)
- 1996 and 2001 Usually Resident Population estimates as extracted respectively from the 1996 and 2001 Censuses of Population and Dwellings (Statistics New Zealand, 1996c, 2001c)
- 1998 Sub-National Usually Resident Population estimates as extracted from Hot off the Press (Statistics New Zealand, 1998k)
- 1996, 1998 and 2001 Labour Cost Index (Statistics New Zealand, 1996f, 1998f, 2001f)
- 1996, 1998 and 2001 Producer's Price Index Outputs as extracted from Key Statistics (Statistics New Zealand, 1996f; 1998f, 2001f)
- 1996, 1998 and 2001 GDP Series for 25 industries from INFOS (Statistics New Zealand, 1996e; 1998d, 2001d)
- 1998 and 2001 International trade statistics as extracted from the New Zealand Harmonised System Classification 1996 (Statistics New Zealand, 1998e, 2001e)
- 1996 and 1999 Agricultural Statistics (Statistics New Zealand, 1998a, 2001a)

5.1.3 Update of the New Zealand Input-Output Model

In this Section the national 1996 inter-industry study of the New Zealand economy (Statistics New Zealand, 2001g) is updated to the year ending 31 March 1998. The national supply and use tables are updated for volume, price and productivity changes. Superior data for the 1998 year covering the primary input and final demand categories are also inserted.

Step 1 Pre-update Aggregation

In mid 2001, SNZ's National Accounts division produced an interim release of the 1996 Inter-industry Study of the New Zealand Economy (Statistics New Zealand, 2001g). This study covered 126 economic industries and 210 economic commodities, along with standard primary inputs and final demands. Industry definitions were based on the Australia New Zealand Standard Industrial Classification (ANZSIC), while commodity definitions were based on the Australia New Zealand Commodity Classification (ANZCC). The base tables were aggregated from 126 industries to 123 industries to ensure that each industry was built up from a unique combination of ANZSIC definitions which, in turn, permitted matching with other statistical datasets (e.g. Business Directory, Capital Accounts, Household Economics Survey, and Harmonised System) and pre-existing environmental accounts. The commodity definitions required no modifications.

Step 2 Volume, Price and Productivity Update

Input-output studies, including those produced by SNZ, are invariably out of date due to the significant time needed for processing surveys. Consequently, updating is usually required for at least volume, price and productivity changes (Jensen *et al.*, 1979; Butcher, 1985; Kerr *et al.*, 1986; Jensen and West, 1988). Given a base year of 1998 for the static analysis, it was necessary to update tables from 1996 to 1998.

The key step in updating the national tables for volume, price and productivity changes is a simple transformation mapping the national gross output vector from $\boldsymbol{\beta}^{1996}$ to $\boldsymbol{\beta}^{1998}$. Mathematically, the update can be expressed as:

$$\beta_i^{1998} = \overbrace{emp_i}^{1998}\left(\frac{\beta_i^{1996}}{\overbrace{emp_i}^{1996}}\right)\frac{\left(\dfrac{\overbrace{gdp_i}^{1998}}{\overbrace{emp_i}^{1998}}\right)}{\left(\dfrac{\overbrace{gdp_i}^{1996}}{\overbrace{emp_i}^{1996}}\right)}\left(\frac{\overbrace{ppi_i}^{1998}}{\overbrace{ppi_i}^{1996}}\right), \tag{5.1}$$

$\overbrace{emp_i}^{1996} \neq 0$, $\overbrace{gdp_i}^{1996} \neq 0$ and $\overbrace{ppi_i}^{1996} \neq 0$,

where $\overbrace{\mathbf{emp}}(\Gamma \text{ x } 1)$ represents FTE employment, $\overbrace{\mathbf{gdp}}(\Gamma \text{ x } 1)$ represents GDP (in constant prices), and $\overbrace{\mathbf{ppi}}$ $(\Gamma \text{ x } 1)$ the Producer's Price Index for Outputs for industry *i* (the overbar $\overbrace{\quad}$ is used to denote a single mathematical term). The superscripts differentiate the 1996 and 1998 financial years. The first two terms on the right hand side of Equation 5.1 update gross output for volume changes, assuming that changes in FTE employment are a reasonable proxy of actual volume change. The third term is a simple productivity estimate based on the ratio of GDP contribution per FTE in 1996 to its equivalent in 1998. The final term is a price inflator which converts the results of the first three terms from 1996 into 1998 dollars.

Step 3 Primary Inputs and Final Demands Update

A common theme in the input-output regionalisation literature is that superior data must be inserted wherever possible (Jensen and West, 1988; Jackson, 1998; Lahr, 2001). Updating the primary inputs, **W**, final demand, **S** and **T**, and trade, **X** and **Y**, components of the accounting framework provided an opportunity for the insertion of superior data. Beginning with trade, **X** and **Y**, Harmonised System commodity imports and exports for 1998 were directly matched to the 123 industry and 210 commodity definitions of the accounting framework using concordances provided by SNZ's (B. Voice, pers. comm., 21 Nov 2001). The 'taxes on products' primary input essentially represents import duties and was updated by assuming that the ratio between imports and duties in each industry remained constant between 1996 and 1998.

The updating of the primary inputs matrix, $\mathbf{W}$, was more cumbersome. Although SNZ regularly produces estimates of primary inputs in its *Key Statistics* publication, these are only released at a highly aggregated industry level. It was therefore not possible to use these data directly in the updating process: however it was used to cross-check results, and in some cases to make *ad hoc* adjustments.[130] Given that wages and salaries represented approximately 40 percent of total primary inputs across all industries, and are a critical determinant of induced (consumer-spending) effects in Type II multipliers, it was considered essential that this category be updated. Specifically, wages and salaries, $\mathbf{W}_{ws}$, in each industry j, were updated in the following manner,

$$w_{ws,j}^{1998} = \widehat{emp}_j^{1998\,\prime} \left(\frac{w_{ws,j}^{1996}}{\widehat{emp}_j^{1996\,\prime}} \right) \left(\frac{\widehat{lci}_j^{1998\,\prime}}{\widehat{lci}_j^{1996\,\prime}} \right), \quad \widehat{emp}_j^{1996} \neq 0 \text{ and } \widehat{lci}_j^{1996} \neq 0, \qquad (5.2)$$

where $\widehat{\mathbf{lci}}$ (Γ x 1) represents SNZ's Labour Cost Index. Each remaining primary input, $\mathbf{W}_{opi}$ (e.g. operating surplus, consumption of fixed capital, other taxes on production and subsidies), in each industry j, was updated by assuming that only relative change had occurred between 1996 and 1998,

$$w_{opi,j}^{1998} = w_{opi,j}^{1996} \left(\frac{\widehat{gdp}_j^{1998\,\prime}}{\widehat{gdp}_j^{1996\,\prime}} \right) \left(\frac{\widehat{ppi}_j^{1998\,\prime}}{\widehat{ppi}_j^{1996\,\prime}} \right), \quad \widehat{gdp}_j^{1996} \neq 0 \text{ and } \widehat{ppi}_j^{1996} \neq 0\,. \qquad (5.3)$$

Unlike the primary input by industry data produced by SNZ, no equivalent dataset is produced for final demand. Fortunately, SNZ does however regularly produce total estimates for the final demand categories. This permitted only a simple *pro-rata* scaling of each final demand category – the approach used in this thesis. In the context of estimating regional final demands, Stevens *et al.* (1983), Treyz and Stevens (1985) and Treyz and Petraglia (2001) all discuss an alternative econometric approach which could be adopted to determine each component of final

[130] Despite the highly aggregated nature of this data, a few industries had one-to-one definitional matches with the 123 industries, enabling direct insertion of the superior data.

demand at the national level. This method relies on estimates of disposable income, intermediate activity and other factors.

Step 4 Matrix Balancing

Once volume and price updates for gross output totals, primary inputs, final demand and trade totals had been established, the national use and supply tables were balanced using the bi-proportional $\mathbf{R\hat{A}S}$ technique (refer to Appendix D for a worked example). It was assumed that the supply matrix coefficients remained the same between 1996 and 1998, allowing the use matrix to be balanced using the $\mathbf{R\hat{A}S}$ technique. Several coefficients in the national use and supply tables were known accurately and were thus left out of the $\mathbf{R\hat{A}S}$ update.[131]

5.1.4 Regionalisation of the New Zealand Model to Generate an Auckland Region Model

Lahr (2001) asserts that the regional economics literature, with the exception of Jackson (1998), is "devoid of any blow-by-blow narrative of the development of regional accounts in a commodity-by-industry setting". Perhaps the most significant limiting factor in the development of commodity-by-industry matrices has been the paucity of specific regional data. This is certainly the true for Auckland Region where only a modicum of regional statistical data is available. It is therefore not surprising that the methodologies developed to date (e.g. Jackson (1998) and Lahr (2001)) have tended to be pragmatic. Similarly, in this study, emphasis is placed on applications of the resulting matrices rather than on the creation of data itself.

Several guiding principles have emerged for the regionalisation of industry-by-industry models. These principles are equally applicable to the regionalisation of commodity-by-industry models: (1) use as much sectoral detail as is available to minimise the impact of aggregation bias[132] (Sawyer and Miller, 1983; Stevens and Lahr, 1993; Lahr, 2001); (2) assume technology is spatially invariant within a nation thereby enabling direct application of raw use coefficients, albeit with some adjustments (Isard, 1951; Lahr, 2001); and (3) regionalisation should be performed on domesticated national accounts[133] (Sawyer and Miller, 1983; Jackson, 1998).

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[131] Updating after removing known or troublesome coefficients is not a new approach; it has been used at least since Paelinck and Waelbroeck (1963), who found the approach produced significantly better tables than the unadjusted $\mathbf{R\hat{A}S}$.

[132] Aggregation bias manifests itself through improper specification of regional industry mix when aggregating.

[133] Most regionalisation methodologies are unable to account for international trade (Lahr, 2001). Thus, regionalisation is only undertaken on domestic coefficients and international trade must be estimated independently.

These principles are applied in the generation of the Auckland Region commodity-by-industry model.

Step 5 Estimation of Regional Output

The core task in any input-output regionalisation methodology is estimating a region's ability to supply its own requirements. Ultimately this information contributes to the estimation of regional imports and exports. Once coefficients have been estimated, regional commodity and industry output must be derived in order to generate commodity/industry balance equations. As with many national statistical agencies, SNZ does not produce sub-national output figures for industries or commodity groupings therefore these must be estimated.[134] Sectoral estimates of regional output are often produced by assuming productivity does not vary among sub-national regions. Simple estimates, based on the Kendricks-Jaycox proportional scaling, have been used here i.e. regional output in each industry i is estimated by scaling the national output, β_i, based on the region's share of national employment for the financial year ending 1998, denoted $\overline{emp}_i^r \in \overline{emp}_i$. Thus,

$$\beta_i^r = \frac{\overline{emp}_i^r}{\overline{emp}_i} \beta_i, \ \overline{emp}_i \neq 0, \tag{5.4}$$

where the superscript r represents a region.[135] If reliable estimates of region-to-nation productivity exist these may also be incorporated,

$$\beta_i^r = \frac{\overline{emp}_i^r}{\overline{emp}_i} \overline{prod}_i^r \beta_i, \ emp_i \neq 0, \tag{5.5}$$

[134] One promising approach is the use of scaled national coefficients based on SNZ's recently released regional GST sales and purchases figures. Current limitations of this approach include how to deal with: (1) businesses that earn under $40,000 per annum, the minimum turnover required for GST registration; (2) sales and purchases of businesses, which are currently included in the GST figures; (3) limited industry disaggregation; and (4) accounting for the zero-rated GST sales of service industries.

[135] The exception is the owner-occupied dwellings industry, which represents the imputed rental value of owner-occupied dwellings, and therefore has no associated employment. This industry's output was estimated by multiplying the number of owner-occupied dwellings by the following scalar, $\frac{\overline{amr}^{1998}}{\overline{amr}^{1996}}$, where $\overline{amr}$ represents the average market rental ($ per week) for Auckland Region.

where $\overset{\frown}{\mathbf{prod}}^{r}$ (Γ x 1) is a regional productivity vector. The ratio of regional to national labour productivity (measured in income per worker), on an industry basis, was the only productivity adjustment made here.

Step 6 Derivation of the Regional Supply Matrix

The national supply matrix, **V**, is regionalised by applying a row-only reduction scalar based on modified SLQs. This assumes, among other things, that the mix of commodities produced by an industry is spatially invariant, an approach that parallels Isard's (1951) industry technology assumption. Analytically, the first step in regionalising the supply matrix is to construct a direct requirements coefficient matrix, **B**. This matrix is analogous to the relationship given by a conventional inter-industry technical coefficients matrix. The formal representation, as determined in Equation 4.33, is

$$\mathbf{B} = \mathbf{V}\hat{\boldsymbol{\alpha}}^{-1}.$$

The coefficient representing the direct requirements for national supply may be adjusted for both competitive and non-competitive imports using the SLQ approach. Firstly, this requires that row coefficients be set to zero in industries where production does not occur i.e. for non-competitive imports, if $\overset{\frown}{emp}_i^{r}=0$ then $\mathbf{B}_i^r=0$. Secondly, row coefficients for industries assumed to be capable of satisfying local demand are left unchanged, i.e. if $\overset{\frown}{slq}_i >= 1$ then $\mathbf{B}_i^r = \mathbf{B}_i$. Finally, the remaining row coefficients of matrix **B**, those assumed incapable of satisfying local demand (i.e. $\overset{\frown}{slq}_i < 1$), are reduced to a regional level using,

$$b_{ij}^r = \overset{\frown}{slq}_i b_{ij}, \qquad (5.6)$$

where $\overset{\frown}{slq}_i$ is the simple location quotient for industry *i*.[136]

Ideally, output estimates would be used to calculate the SLQs. As noted previously, regional output estimates are not readily available in New Zealand. Employment was therefore used as a proxy for output. Employment estimates, measured in FTEs, were derived from SNZ's

[136] The difference between b_{ij} and b_{ij}^r when $\overset{\frown}{slq}_i < 1$ is attributed to regional imports in step 10.

Business Directory for each of the 123 industries.[137] To improve the accuracy of the regional output estimates, management structures were excluded from non-service based industries in the calculation of SLQs. This facilitated the elimination of anomalies resulting from the presence of head office management structures. Applying unadjusted Auckland Region forestry FTEs in SLQ calculations would, for example, result in erroneous output estimates due to the presence of head office management.[138]

The use of employment as a surrogate for output however introduces inaccuracies. One major drawback of using employment figures as surrogates, for example, is that productivity differences (i.e. output per FTE) between the region and nation are overlooked. A further limitation is that because the Business Directory represents annualised FTEs the seasonal trends which affect agricultural industries and, through flow-on effects, their associated processing industries are misrepresented. Where possible, *ad hoc* adjustments were made to the Business Directory FTEs to minimise the impact of this discrepancy using Agriculture Statistics (Statistics New Zealand, 1998a, 2001a), Labour Force Survey (Statistics New Zealand, 1998g) and Census of Population and Dwellings (Statistics New Zealand, 1996c, 2001c) data.

Over the past three decades, a substantial body of literature has hotly debated the costs and benefits of using SLQs to regionalise national input-output models (refer to *inter alia* Richardson (1972), Morrison and Smith (1974), McMenamin and Haring (1974), Round (1983), Sawyer and Miller (1983), Jensen *et al.* (1979) and Stevens *et al.* (1989)). On the one hand, analysts have found that coefficients adjusted by location quotients compare favourably with actual coefficients (Schaffer and Chu, 1969; Morrison and Smith, 1974; Jensen *et al.*, 1979; Sawyer and Miller, 1983). On the other hand, analysts have criticised the application of location quotients on theoretical grounds, in particular, on the ability of such a simple construct to adequately reflect the complex interrelationships that exist in an economy (Miernyk, 1968, 1969, 1976; Round, 1983; Stevens *et al.*1989).[139] The SLQ technique has been applied here in the absence of data suitable for any of the other approaches reviewed in Appendix D.

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[137] For owner-occupied dwellings, national coefficients were used as regional substitutes.

[138] A recent survey by Deloitte and Touche Consulting Group (1997) ranked the top 200 New Zealand businesses according to actual turnover; it found that 96 of those businesses were located within the Auckland Region. Of these, nearly all represented head offices, many of which have their principal activities located elsewhere in New Zealand.

[139] Mayer and Pleeter (1975) offer theoretical justifications for the use of location quotients.

Step 7 Estimation of Regional Value Added

Crude estimates of regional value added may be derived by scaling each industry in the national value added matrix by its corresponding share of national output.

$$\breve{w}_{ij}^{r} = \frac{w_{ij}}{\beta_j{}'}\beta_j^{r}{}', \ \beta_j{}' \neq 0. \tag{5.7}$$

Note that the concave over-bar ˘ in the left-hand term of Equation 5.7 signifies that, for the time being, it is only an estimate.

Sawyer and Miller (1983) have identified that a large percentage of error in non-survey tables is attributable to inaccuracies in estimating value added coefficients, particularly wages, salaries and proprietor's income. Jensen and West (1980), among others, have shown that the accuracy of large coefficients, such as wage and salary coefficients, in a direct requirements matrix, is a critical determinant of the accuracy of the matrix's Leontief inverse. Moreover, wages and salaries are required for the calculation of induced economic impacts brought on by consumer spending. Accurate estimation of this component is therefore particularly crucial. Fortunately, SNZ's Census of Population and Dwellings (Statistics New Zealand, 1996c, 2001c) provides estimates of mean wage/salary earnings per worker (FTE) by disaggregated industry and spatial location. Implementation is as follows,

$$\mathbf{W}_{ws}^{r} = \left(\overbrace{\mathbf{incpw}}^{r} \times \overbrace{\mathbf{emp}}^{r} \right)', \tag{5.8}$$

where $\overbrace{\mathbf{incpw}}^{r}$ is a Γ x 1 vector of regional labour income per worker (as measured in \$ per FTE).[140]

No reliable estimates of the remaining value added categories exist at the regional level. Instead the remaining components are recalibrated as suggested by Lahr (2001) based on the wages and salaries row inserted in Equation 5.8. Wages and salaries are first subtracted from value added, and then the difference is redistributed to the remaining components of value added, keeping fixed each component's share of non-wage and salary value added,

[140] For simplicity, in the context of vectors, the usual algebraic representation of a ratio is used to represent a Hadamard scalar (element-by-corresponding-element) ratio. Similarly, the multiplication symbol, ×, is used to denote Hadamard scalar (element-by-corresponding-element) multiplication.

$$\mathbf{W}^r_{opi}=\left(\mathbf{i}'\breve{\mathbf{W}}^r-\mathbf{W}^r_{ws}\right)\times\frac{\breve{\mathbf{W}}^r_{opi}}{\left(\mathbf{i}'\breve{\mathbf{W}}^r-\breve{\mathbf{W}}^r_{ws}\right)'},\ \mathbf{i}'\breve{\mathbf{W}}^r-\breve{\mathbf{W}}^r_{ws}\neq 0, \tag{5.9}$$

where the subscript *opi* denotes a given non-wage and salary value added row. Thus, regional value added, $\mathbf{W}^r$, is a concatenation of Equations 5.8 and 5.9. Note that the concave overbar has been removed from the left hand side of Equation 5.9 signifying that it is no longer an estimate.

Step 8 Derivation of the Regional Use Matrix

Once regional output and value added has been estimated, the region's use matrix may be derived. However, the so-called 'fabrication adjustment' must first be applied to the national use table in direct requirements coefficient format i.e. $\mathbf{Б}=\mathbf{U}\hat{\boldsymbol{\beta}}^{-1}$. This requires that regional output, $\boldsymbol{\beta}^r$, less regional value added, $\mathbf{W}^r$, equals regional intermediate use for each industry, i.e. $\mathbf{i}'\mathbf{Б}^r+\left[\left(\mathbf{i}'\mathbf{W}^r\right)/\boldsymbol{\beta}^{r}{}'\right]=1$, where $\boldsymbol{\beta}^{r}{}'\neq 0$. This is performed by rescaling the columns of $\mathbf{Б}$ to account for known regional output and value added,

$$\breve{\mathbf{U}}^r=\mathbf{Б}\widehat{(\mathbf{i}'\mathbf{Б})}^{-1}\left[\hat{\boldsymbol{\beta}}^r-\widehat{\left(\mathbf{i}'\mathbf{W}^r\right)}\right]. \tag{5.10}$$

The concave over-bar once again reminds us that $\breve{\mathbf{U}}^r$ is only an estimate and that superior data could be inserted where available.

Step 9 Estimation of Regional Final Demand

The national final demand matrices, **S** and **T**, must also be modified to approximate regional equivalents, $\mathbf{S}^r$ and $\mathbf{T}^r$. Treyz and Stevens (1985) argue that the coefficients of regional final demand may be estimated using an econometric approach dependent on regional disposable income, intermediate demand, and several other factors. The lack of specific Auckland Region data makes any attempt to derive regional final demand estimates using this approach almost futile. Final consumption expenditures, excluding household consumption (private non-profit institutions serving households, central government and local government) were considered dependent on domestic supply and, moreover, a function of regional population size. Thus, the final consumption expenditure columns of matrices **S** and **T** were reduced to the regional level by multiplying each matrix element by the ratio of regional-to-national population

$$\kappa^{r}_{i,ofd} = \kappa_{i,ofd}\left(\frac{\overbrace{pop}^{r}}{\overbrace{pop}}\right), \quad \overbrace{pop} \neq 0 \tag{5.11}$$

where **K** represents **S** and **T** augmented i.e. **S|T**, $\overbrace{pop}$ denotes a population scalar, and *ofd* represents either expenditure on private non-profit institutions serving households, central government expenditure, or local government expenditure. Similarly, household consumption was considered a function of the number of households, $\overbrace{hhlds}$, and concomitantly household income, $\overbrace{ahi}$.[141] Again, where superior data were known, they were inserted in place of the scaled entries. Thus, $\mathbf{K}^{r}_{hc}$ was determined as follows,

$$\kappa^{r}_{i,hc} = \kappa_{i,hc}\left[\left(\frac{\overbrace{hhlds}^{r}}{\overbrace{hhlds}}\right)\left(\frac{\overbrace{ahi}^{r}}{\overbrace{ahi}}\right)\right], \quad \overbrace{hhlds} \neq 0 \text{ and } \overbrace{ahi} \neq 0, \tag{5.12}$$

where the subscript *hc* represents the household consumption final demand column.

The most difficult final demand activities to regionalise were gross fixed capital formation and change in inventories. It is likely that a significant proportion of regional capital investment lies in construction expenditure; however, other forms of investment demand may also exist. Despite the fact that changes in inventories may be tracked by industry at a national level, no such data exists to undertake this at a regional level. Instead, changes in inventories, $\mathbf{K}^{r}_{ci}$, are calculated as,

$$\mathbf{K}^{r}_{ci} = \mathbf{K}_{ci}\left(\frac{\mathbf{Ui}^{r}}{\mathbf{Ui}}\right), \quad \mathbf{Ui} \neq 0, \tag{5.13}$$

where the subscript *ci* denotes the changes in inventories final demand column. In this way, changes in inventories are estimated by assuming that the national ratio of changes in inventories to the industries in the use matrix is equivalent to that of the region.

[141] A more conceptually appealing adjustment based on SNZ's Household Economic Survey (HES), which matched regional household types with household spend by commodity group, was also pursued. This approach parallels SNZ's own method of compiling household consumption at the national level; however this approach was stymied as SNZ would not release a concordance matching HES commodity definitions to input-output commodity definitions.

To complete the regionalisation of the final demand, estimates must be calculated for the value added into final demand matrices, **R** and **Z**. To facilitate this calculation, **R** and **Z** are first augmented to form Д i.e. Д = **R** | **Z**.

Value added inputs into household consumption, $Д^r_{hc}$, are generated in a similar manner to commodity inputs into household consumption (as per Equation 5.12),

$$Д^r_{i,hc} = Д_{i,hc}\left[\left(\frac{\overline{hhlds}^r}{\overline{hhlds}}\right)\left(\frac{\overline{ahi}^r}{\overline{ahi}}\right)\right],\ \overline{hhlds} \neq 0 \text{ and } \overline{ahi} \neq 0, \qquad (5.14)$$

where the value added inputs into the remaining final demand categories, $Д^r_{nhc}$, were estimated by assuming that for each value added category the ratio of regional to national value added into non-household consumption final demand is equivalent, for each corresponding category, to that of regional to national value added,

$$Д^r_{nhc} = Д_{nhc} \times \left(\frac{\mathbf{W}^r\mathbf{i}}{\mathbf{Wi}}\right), \mathbf{Wi} \neq 0, \qquad (5.15)$$

where *nhc* represents a given non-household final demand category.

Step 10 Estimation of Regional Inflow and Outflow

International imports into Auckland Region are partly a function of interregional demand for each commodity. While it may be assumed that Auckland Region utilises international imports in proportion to its share of non-export demand, local production and demand patterns should also be taken into consideration. However, a paucity of regional specific data again prohibited consideration of these patterns. It was instead assumed that international imports by each regional industry did not vary relative to their national equivalents, thus,

$$y^{*r}_{ij} = y^*_{ij}\left(\frac{\overline{emp_j}^{r\,\prime}}{\overline{emp_j}^{\prime}}\right),\ \overline{emp_i} \neq 0, \qquad (5.16)$$

where y^*_{ij} is an element in a В x Г international import matrix, recording commodity *i* imports into industry *j*. Matrix **Y*** was produced as part of Statistics New Zealand's (2001g) interim release of the New Zealand inter-industry study. Note that the vector $\mathbf{Y}_{intimp} = (\mathbf{Y^*i})'$, where *intimp* denotes the international imports row. International exports from Auckland Region, $x^{r}_{i,intexp}$ where the subscript *intexp* denotes international exports, were calculated in a similar manner to changes in inventories and gross fixed capital formation (refer to Equation 5.13).

By comparison, regional economies are generally more open than their national counterparts (Richardson, 1972; Jensen *et al.* 1979; Lahr 2001). To account for interregional trade, inflows and outflows of commodities must also be evaluated. Ideally, this would be achieved by surveying of the origins and destinations of traded commodities within the nation. Time constraints precluded a survey; instead the industry-based rows-only location quotient approach, as employed in deriving the regional supply matrix, was used to generate crude estimates of interregional trade.[142] Specifically, the difference between the regional direct requirements coefficient, $b^{r}_{i,j}$, as calculated by Equation 5.6, and the national direct requirements coefficient, $b_{i,j}$, provides a measure of the size of the interregional import coefficient, for those industries unable to satisfy local demand (i.e. $\widehat{slq_i} < 1$). This assumes that the regional and national direct requirements coefficients differ only by the size of interregional imports.[143] In turn, the coefficient may be converted to a transaction value ($) by multiplying by α^{r}_{i}, i.e.

$$\mathbf{Y}_{regimp} = (\mathbf{i}'\mathbf{B} - \mathbf{i}'\mathbf{B}^{r})\boldsymbol{\alpha}^{r'}. \tag{5.17}$$

This approach has been widely used by input-output analysts in non-survey regionalisation of industry-by-industry matrices (Richardson, 1972; Jensen *et al.*, 1979; Jensen and West, 1980; Butcher, 1985; Kerr *et al.*, 1986; Jensen, 1990), and is adapted here for use with commodity-by-industry matrices.

Step 11 Final Adjustments

With estimates by commodity of regional output, $\boldsymbol{\alpha}^{r}$, final demand, $\mathbf{K}^{r}$, regional outflows, $\mathbf{X}^{r}$, and inflows, $\mathbf{Y}^{r}$, and by industry of regional output, $\boldsymbol{\beta}^{r}$, and value added, $\mathbf{W}^{r}$, the regional use matrix, $\mathbf{U}^{r}$, was re-estimated using the $\mathbf{R\hat{A}S}$ technique to ensure table balance. The $\mathbf{R\hat{A}S}$ technique is widely utilised by national statistical agencies, including SNZ (2001g), as a final step in balancing input-output tables.

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142 Chapter 8 and Appendix C investigate this problem further.

143 By corollary, if the slq_i>1 then the contribution made in each element of row i to interregional exports may be derived as $\left(\left(b_{i,j} \times \widehat{slq_i}\right) - b_{i,j}\right)\beta'_j$.

Once the final matrices have been constructed two additional tasks are commonly performed to facilitate further analysis. Firstly, a industry-by-industry (institutional) matrix for the region may be derived using the algebraic steps outlined in Section 4.4.3.2. Secondly, industries and commodities may be aggregated to form matrices that are significantly easier to manipulate analytically and, more importantly, these matrices are easier to interpret.[144] Several collapsible resolutions of mutually compatible definitions were developed, allowing for a variety of intended purposes. Specifically, matrices were generated for 123, 48, 35 and 23 industry classifications and 210, 48 and 35 commodity classifications. Concordances showing the relationships between the various aggregate definitions and the ANZSIC and ANZCC statistical definitions are provided in Appendix E.

The completed commodity-by-industry models for New Zealand and Auckland Region for the year ending 31 March 1998 are available as two Excel files ('New Zealand Commodity-by-Industry Model.xls' and 'Auckland Region Commodity-by-Industry Model.xls') in the Chapter 5 directory of the accompanying CD-ROM. These have been aggregated from 123 industries by 210 commodities to 48 industries by 48 commodities. Also included on the CD-ROM are standard Leontief input-output tables for New Zealand and Auckland Region ('New Zealand Input-Output Model.xls' and 'Auckland Region Input-Output Model.xls'), converted from 123 industries by 210 commodities to 123 industries by 123 industries under the industry-based technology assumption described in Section 4.4.3.2, and then aggregated to 48 industries by 48 industries. The commodity-by-industry matrices, further aggregated to 3 commodities by 3 industries, and the standard Leontief input-output tables for New Zealand and Auckland Region, aggregated to 3 industries by 3 industries, are presented in Appendix F.

5.1.5 Limitations of the Auckland Region Economic Input-Output Model

The methodology for deriving the commodity-by-industry model has, among other things, incorporated superior data, particularly: (1) modified regional output estimates based on the exclusion of management structures from non-service based industries, (2) the inclusion of regional productivity estimates, and (3) the inclusion of region specific *ad hoc* data. Despite these improvements, several major limitations of the national update and regionalisation procedure remain leading to imprecise calculation of Auckland Region's commodity-by-industry model:

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[144] Aggregation must be undertaken with care to avoid unnecessary loss of data. Minimally aggregation should consider (1) the intended purpose of the tables, (2) peculiarities in regional economic make up, including physical and political boundaries or impediments to trade, and (3) the user's ability to interpret meaningfully the information embedded within the tables.

- *Cross-hauling*. The use of SLQs permits only estimation of net outflows in a region. This assumption is naïve and underestimates gross imports and exports from other regions resulting in overestimates of interdependence, and as a corollary, inflated multipliers.
- *Multi-region consistency*. The method aims to construct of a single set of supply, use and inter-industry matrices for one particular region. Additional issues, such as consistency across a multi-regional framework, require further research effort.
- *Self-sufficiency*. The SLQs applied in the regionalisation assume maximum self-sufficiency in each intermediate demand industry; this, in turn, leads to overestimation of coefficients and inflated multipliers.
- *Industry technologies*. The national supply table is based on industry production technologies that represent an average for all regions in the nation. Regional production technologies can however vary considerably due to factors such as age of capital stock, relative prices and resource availability.
- *Consumption and investment patterns*. National and regional consumption patterns may differ substantially, particularly in consumer preferences and household income. Moreover, capital investment patterns are inherently volatile, and changes in inventories are often due to factors exogenous to the regional economy, e.g. international investment decisions.

5.1.6 Accuracy of the Auckland Region Economic Input-Output Model

The overarching issue in assessing the performance of any regionalisation method is how to evaluate accuracy. Partitive assessment of accuracy would require a cell-by-cell comparison with survey-based tables.[145] Cell-by-cell accuracy has been assessed using various statistical techniques including Chi-square, correlation, regression analysis, and Theil coefficients (Schaffer and Chu, 1969, 1971). The absence of any survey-based table in Auckland Region however makes this infeasible. Holistic accuracy, first coined by Jensen (1980), is perhaps a better measure of the accuracy of the input-output matrices created here. A holistic approach suggests that table accuracy may be viewed as a portrait, which reflects characteristics of the economy in question, both in terms of structure and function (Jensen, 1980; West *et al.*, 1980; Jensen *et al.*, 1988). Moreover, it attempts to derive comprehensive 'whole table' concepts from the overwhelming data contained within input-output tables. Such concepts include (1)

[145] However, survey-based tables are not without their own problems, including (1) survey design errors, (2) incorrect coding at the firm level, (3) misreporting of sale and purchase figures, (4) data handling errors, and (5) in the case of compiling industry-by-industry model, errors through the use of commodity, industry or hybrid technology assumptions.

the contribution of the various constituent matrices to the whole, (2) emphasis on "the main features of the economy in terms of size and structure, with the analytically-less-important features treated as background" (Jensen, 1980, p.142), (3) the movement from fine-grained disaggregated to course-grained aggregated tables, and (4) new methods for table classification based on the development of a typology of economies.

Two tests were conducted on the Auckland Region commodity-by-industry framework for holistic accuracy. In the first test, key table indicators such as gross output, GRP balance of trade, and Type I and Type II value added and employment multipliers were compared with independent estimates generated by Butcher Partners Limited (BPL).[146] BPL is acknowledged as the main provider of regional input-output tables in New Zealand. BPL utilises the GRIT methodology, developed by Jensen *et al.* (1979), Jensen and West (1988), and West (1990) at the University of Queensland, to produce regional input-output tables. A full description of the national update and regionalisation procedure used by BPL is available in Butcher (1985). Multiplier comparisons were made for the 48 aggregated industries[147] for the updated national and Auckland Region input-output models.[148]

At the national level, comparisons of economy-wide gross output and GDP compared favourably. Total gross output in the New Zealand economy was estimated by BPL to be $392,816 million, while the methodology developed here produced an estimate of $388,647 million – a difference of 1.06 percent. Estimates of national GDP were also close at $113,078 million (BPL) and $112,315 million (this study), a difference of $762 million or 0.67 percent. A comparison of Type I and Type II value added multipliers produced less convincing, albeit still comparable, results. It was found that 73 percent of Type I value added multipliers, for example, were within 20 percent of the BPL estimate, and that the average difference (in absolute terms) was 16 percent. Of the Type II value added multipliers, 69 percent (33 industries) were within 20 percent of the BPL estimates, that 8 percent (4 industries) recorded differences of between 50 and 70 percent[149], and that the average percentage difference (in absolute terms) was 17 percent. A correlation analysis of the Type I and II employment

[146] A necessary prerequisite for this task was the conversion of the commodity-by-industry matrices to an industry-by-industry form. This was achieved using an industry technology assumption as outlined in Section 4.4.3.2.

[147] Slight differences in industry definitions meant that two industries (Construction [29] and Electricity [26]) were not strictly comparable.

[148] The comparisons recorded here are for the year ending 31 March 2001, rather than the 1997-98 study year. Nevertheless, the methodology used in construction of the 2000-01 industry-by-industry table is the same. Using a 2000-01 table for comparison is likely to lead to inaccuracies in the national update phase of the methodology, as greater structural change will have occurred between 1995-96 and 2000-01, than between 1995-96 and 1997-98.

[149] This included Construction [29], one of the two industries not strictly comparable with the BPL industries.

multipliers generated by BPL and through this study (across the industries) produced correlation coefficients at 0.84 (Type I) and 0.87 (Type II). Thus, differences in the Type I and II employment multipliers were less dramatic than for the value added multipliers, with 81 percent of both Types within 20 percent of the BPL equivalents.

In the regional comparison, gross output and GRP for the economy also compared well, differing from BPL estimates respectively by 0.5 percent ($694 million) and -2.0 percent (-$754 million). Interregional trade also showed a small discrepancy with imports differing by 2.2 percent and exports by -3.2 percent. The comparison of value added and employment multipliers with BPL equivalents compared well, showing a high degree of correspondence. Type I and Type II value added multipliers differed slightly, with 71 percent of both Types falling within 20 percent of BPL estimates, and only one industry differing by between 50 and 60 percent. Similarly, 79 percent of Type I and 75 percent of Type II employment multipliers varied from BPL figures by 20 percent or less, generating correlation coefficients of 0.69 and 0.68 respectively.

In the second test, large coefficients in the commodity-by-industry direct requirements matrices were identified, and those that had been estimated by superior data were tagged. Of the top 100 largest coefficients, it was found that 73 percent had been derived from superior data. Jensen (1980) and Sawyer and Miller (1983) *inter alia*, have argued that obtaining the highest possible accuracy for large coefficients is essential because these coefficients that contribute most to regional interdependency.

5.2 Structural Analysis of the Auckland Region Economy

5.2.1 Economic Production

The Auckland Region GRP for the year ending 31 March 1998 was estimated to be $33.2 billion, or 34.2 percent of national GDP. The contribution to GRP by the 20 most important industries (out of an aggregated 48) is shown in Table 5.1. The difference in industry rankings between the nation and Auckland Region is also shown. Basic metals manufacture (ranked 28 out of 48), for example, is ranked 12 places higher in the contribution it makes to the Auckland Region economy compared to its national counterpart (ranked 40 out of 48).

Regional industries that ranked well above their national equivalents included Rubber, plastic and other chemical product manufacturing [19]; Beverages, malt and tobacco manufacturing [13]; and Non-metallic mineral manufacturing [20]. Despite the lowering of trade barriers in the 1980s, and a reorientation toward provision of services, these findings corroborate earlier research which identified the region's strength in import substitution, i.e. the repackaging or processing of imported products and their subsequent redistribution to other regions. Given Auckland Region's dominance as the commercial heart of New Zealand, it is also not surprising that primary industries such as Forestry and logging [6], Dairy cattle farming [3], Livestock and cropping farming [2], and downstream Meat and meat product manufacturing [10], are ranked well below national equivalents.

Table 5.1 Contribution to Auckland Region GRP

Industry	Contribution to GRP ($ billion)	Difference in Rank Auckland Region cf NZ
30 Wholesale trade	3,231	2
42 Business services	3,058	-1
41 Ownership of owner-occupied dwellings	2,589	-1
31 Retail trade	1,973	0
40 Real estate	1,833	1
29 Construction	1,442	1
37 Finance	1,350	2
46 Health and community services	1,309	-3
35 Air transport, services to transport and storage	1,223	3
36 Communication services	1,217	0
45 Education	1,062	-3
47 Cultural and recreational services	745	5
17 Printing, publishing and recorded media	676	6
43 Central government administration, defence, public order and safety services	673	-3
19 Rubber, plastic and other chemical product manufacturing	607	10
24 Machinery and equipment manufacturing	598	2
33 Road transport	525	-2
22 Structural, sheet, and fabricated metal product manufacturing	506	9
12 Other food manufacturing	444	2
32 Accommodation, restaurants and bars	389	0
48 Personal and other community services	384	5
38 Insurance	372	8
16 Paper and paper product manufacturing	363	5
14 Textile and apparel manufacturing	354	7
26 Electricity generation and supply	317	-11
39 Services to finance and investment	310	8
44 Local government administration services and civil defence	285	-3
21 Basic metal manufacturing	280	12
13 Beverage, malt and tobacco manufacturing	274	12
23 Transport equipment manufacturing	274	5
20 Non-metallic mineral product manufacturing	267	8
25 Furniture and other manufacturing	264	10
18 Petroleum and industrial chemical manufacturing	204	4
34 Water and rail transport	199	-5
15 Wood product manufacturing	153	-3
1 Horticulture and fruit growing	123	-3
6 Forestry and logging	114	-14
11 Dairy product manufacturing	106	-2
10 Meat and meat product manufacturing	99	-17
3 Dairy cattle farming	90	-27
2 Livestock and cropping farming	69	-25
8 Mining and quarrying	63	2
28 Water supply	59	5
27 Gas supply	58	3
7 Fishing	35	1
4 Other farming	34	-1
5 Services to agriculture, hunting and trapping	25	-4
9 Oil and gas exploration and extraction	8	-10

5.2.2 Contribution to New Zealand GDP

Figure 5.2 shows the 20 most significant industries in Auckland Region's economy arranged in terms of the percentage contribution they make to their equivalent industry in the national economy, as measured in value added terms. This clearly shows Auckland Region's strategic advantage as the main entry point into New Zealand with Air transport, including services to transport and storage [35], comprising more than 55 percent of the national figure.[150] This, coupled with a strong emphasis on light manufacturing, retailing, commerce and provision of services, confirms Auckland Region as the dominant economic region within New Zealand (Deloitte and Touche Consulting Group, 1997). Significant population growth over the last two decades has fuelled several residential property booms, the effects of which are captured in Figure 5.2 with the contributions made by the Real estate [40] and Construction [29] industries. This is reinforced by SNZ (1999b) who note that Auckland Region ranked third out of the nation's sixteen regions in terms of the proportion of businesses involved in the Construction [29] industry.

[150] Because Auckland Region is the main international gateway into New Zealand, its accommodation captures a significant portion of total guest nights; for the 1997 calendar year, this figure was estimated to exceed 3.6 million (16.5 percent of the national total) (Statistics New Zealand, 1999b).

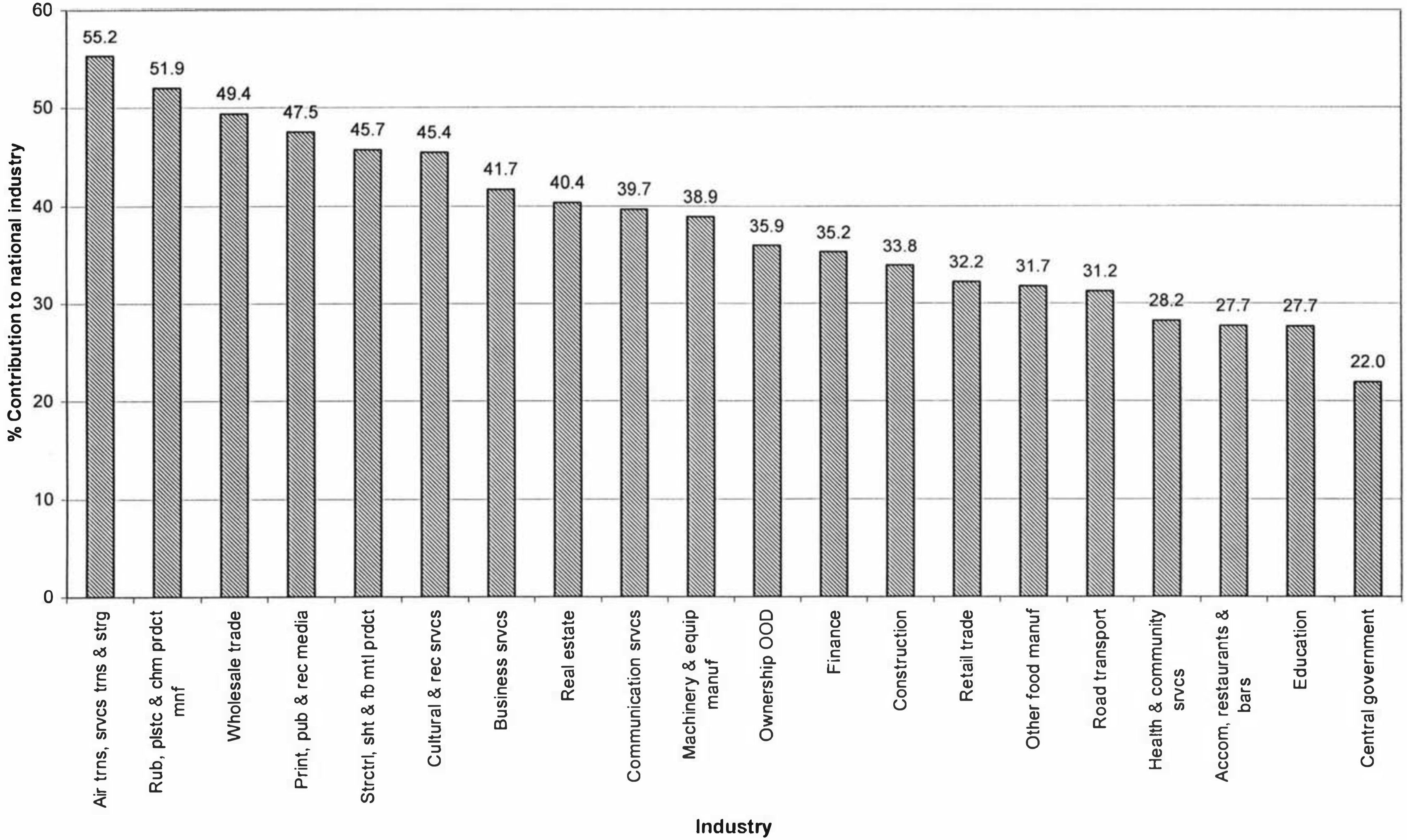

Figure 5.2 **Top Ranking Auckland Region Industries 1997-98 (Percentage Contribution to New Zealand GDP)**

5.2.3 Economic Specialisation and Comparative Advantage

The industries in which Auckland Region has a comparative advantage compared with the rest of New Zealand, can be identified using the SLQs generated in Section 5.2.2. The SLQ approach is generally the most commonly used method of determining the size of a region's basic and non-basic industries[151] (McCann, 2001, p.148) and of measuring the comparative strength or weakness of an industry in a region, relative to the national situation. Accordingly, industries with a SLQ > 1 are, relative to the nation, capable of supplying local demand, and are therefore deemed to be strong industries. Those industries with a SLQ < 1 are, relative to the nation, incapable of supplying local demand and deemed weak industries. Of 48 industries in the Auckland Region economy, 25 have a comparative advantage over the nation (Table 5.2). Again the importance of Auckland Region as the key entry point into New Zealand is highlighted, along with light manufacturing and wholesaling aligned with import substitution, and the general associating of business services with all parts of the economy.

Although the location quotient may be used to specify industries with a comparative advantage over their national counterparts it is also important to consider the size of the industry, as measured by contribution to value added. An analysis of both comparative advantage and size reveals that not only does Auckland Region have 25 industries with comparative advantage, but also 23 of these industries, as a percentage of their national counterparts, contribute more to GRP than the overall Auckland Region economy average of 34.2 percent. Nevertheless, the percentage contribution to overall GRP is small for several industries including Water supply [28] ($59 million or 0.18 percent of GRP), Petroleum and industrial chemicals manufacture [18] ($204 million, 0.62 percent) and Furniture and other manufacturing [25] ($264 million, 0.80 percent). Hence, those industries with a comparative advantage also make a significant value added contribution.

[151] Basic industries tend to operate, be owned, and make decisions at the national or international level. They are often large scale and, in the case of business services, concentrated in high quality office space with skilled staff. Non-basic industries tend to serve local demand and are usually concentrated throughout cities.

Table 5.2 Location Quotients for the Auckland Region Economy

Industry	Simple Location Quotient
35 Air trns, srvcs trns & strg	1.72
19 Rub, plstc & chm prdct mnf	1.62
25 Furniture & other manuf	1.54
30 Wholesale trade	1.54
21 Basic metal manuf	1.53
13 Bev, malt & tobacco manuf	1.53
17 Print, pub & rec media	1.51
22 Strctrl, sht & fb mtl prdct	1.42
39 Srvcs to fnnce & invstmnt	1.31
20 Nn-mtllc mnrl prdct manuf	1.31
40 Real estate	1.30
42 Business srvcs	1.30
28 Water supply	1.28
38 Insurance	1.27
14 Textile & apparel manuf	1.24
36 Communication srvcs	1.23
23 Transport equip manuf	1.23
24 Machinery & equip manuf	1.22
47 Cultural & rec srvcs	1.17
18 Ptrlm & ind chem manuf	1.14
37 Finance	1.10
29 Construction	1.08
16 Paper & paper prdct manuf	1.07
48 Personal & other comm srvcs	1.05
31 Retail trade	1.00
12 Other food manuf	0.99
27 Gas supply	0.98
33 Road transport	0.98
46 Health & community srvcs	0.90
32 Accom, restaurants & bars	0.88
45 Education	0.87
44 Local government	0.71
43 Central government	0.70
34 Water & rail trans	0.65
15 Wood prdct manuf	0.57
26 Elctrcty gnrtn & spply	0.56
11 Dairy prdct manuf	0.48
1 Hort & fruit growing	0.48
8 Mining & Quarrying	0.40
7 Fishing	0.33
4 Other farming	0.30
10 Meat & meat prdct manuf	0.23
6 Forestry & logging	0.16
5 Srvcs to ag, hnt & trppng	0.15
3 Dairy cattle farming	0.13
2 Livestock & cropping	0.13
9 Oil & gas explr & extrc	0.06
41 Ownership OOD[1]	N/A

Note:

1. The output of this industry represents the imputed rental value of owner-occupied dwellings. As this industry has no employment a location quotient cannot be calculated.

5.2.4 Balance of Trade

Auckland Region's combined interregional and international balance of trade was estimated to be $957 million for the year ending 31 March 1998 (Table 5.3). The region was therefore a net exporter of goods and services. By contrast, regional expenditure on international imports, $9,651 million, exceeded revenue generated from international exports, $9,174 million, resulting in a trade deficit of $477 million.[152] Some 33.8 percent (or $3,105 million) of the value of Auckland Region's international exports comprised so called re-exports i.e. goods and services imported from other regions/abroad for export elsewhere.[153] This is not a surprising finding given that Ports of Auckland is the nation's largest cargo port, handling 3.4 million tonnes of exports for the year ending 30 June 1996 (Statistics New Zealand, 1999b). The sizeable export earnings generated from air transport and its associated services is a consequence of the presence of Auckland International Airport, the most active gateway in and out of New Zealand.

Close to 22 percent ($2,120 million) of international imports are purchased by the region's Households [49]. This includes goods imported by local wholesalers/retailers and, in turn, on-sold with an additional markup to households e.g. motor vehicles and computers. The importations of Gross fixed capital [53], particularly plant and machinery, is also significant at $1,571 million. Auckland Region's historical role in import substitution, through final processing, repackaging and redistribution to other New Zealand centres, particularly in the import contributions made by Wholesale trade [30] and the Rubber, plastic and chemical product manufacturing [19] industry. Again, Auckland International Airport's influence is apparent.

Interregional trade is of a similar magnitude to international trade. Importation of international exports for re-export accounts for 33.7 percent of the $9,192 million of interregional imports. Households [49], Central government [51], and Wholesale trade [30] consume $2,501 million (27.2 percent) of goods and services imported from other regions. By comparison, interregional exports amounted to $10,626 million. Principal exporting industries were the Wholesale trade [30], Business services [42] and Air transport *etc.* [35] industries; these account for 43.1 percent (or $4,580 million) of interregional exports. These findings substantiate Auckland Region's claim as New Zealand's commercial hub and key gateway for international travellers, and

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[152] New Zealand as a whole recorded a trade surplus of $343 million for the same period.

[153] Some commentators have noted that it is advantageous for cargo ships destined for Australia to first berth in New Zealand, and in so doing, gain cheaper port handling fees on their arrival in Australia due to the bilateral Closer Economic Relations (CER) agreement between the two nations.

emphasise its national role in import substitution and redistribution. Overall, Auckland Region recorded a significant interregional trade surplus of $1,434 million.

Table 5.3 Auckland Region's Financial Balance of Trade, 1997-98

	Exports	Value		Imports	Value	Balance of Trade
		$ million			$ million	$ million
	Interregional exports			*Interregional imports*		
30	Wholesale trade	2,269	56	International exports	3,105	
42	Business services	1,270	51	Central government	983	
35	Air transport, services to transport and storage	1,041	49	Households	954	
19	Rubber, plastic and other chemical product manufacturing	635	30	Wholesale trade	564	
29	Construction	444	11	Dairy product manufacturing	519	
	Others	4,968		Others	3,068	
	Sub-total	10,626		Sub-total	9,192	1,434
	International exports			*International imports*		
55	Interregional imports	3,105	49	Households	2,120	
11	Dairy product manufacturing	643	53	Gross fixed capital formation	1,571	
35	Air transport, services to transport and storage	562	35	Air transport, services to transport and storage	616	
24	Machinery and equipment manufacturing	472	30	Wholesale trade	511	
14	Textile and apparel manufacturing	426	19	Rubber, plastic and other chemical product manufacturing	403	
	Others	3,966		Others	4,431	
	Sub-total	9,174		Sub-total	9,651	-477
	Total exports	19,800		Total imports	18,843	957

5.2.5 Network Analysis of Financial Flows: Clusters of Comparative Advantage

An analysis of the major financial flows between the top twenty industries with a comparative advantage, as measured in SLQ terms, provides an overall understanding of how the Auckland Region economy is structured (Figure 5.3). The two largest financial inputs for each industry are recorded, along with each industry's gross output (within the boxes).[154] Moreover, the industries are broadly grouped: industries driven by local demand, industries driven by interregional or international export demand, and industries driven by intermediate demand in supporting roles. Placement in each group was determined by calculating the share of each industry's output consumed by local demand, export demand and by other industries. Cross boundary industries are also identified. Several key clusters of comparative advantage are described below.

[154] Only inter-industry flows are considered. Primary inputs, such as wages and salaries, and imports, are not considered – these inputs often constitute 30 to 40 percent of the financial value of total inputs into an industry.

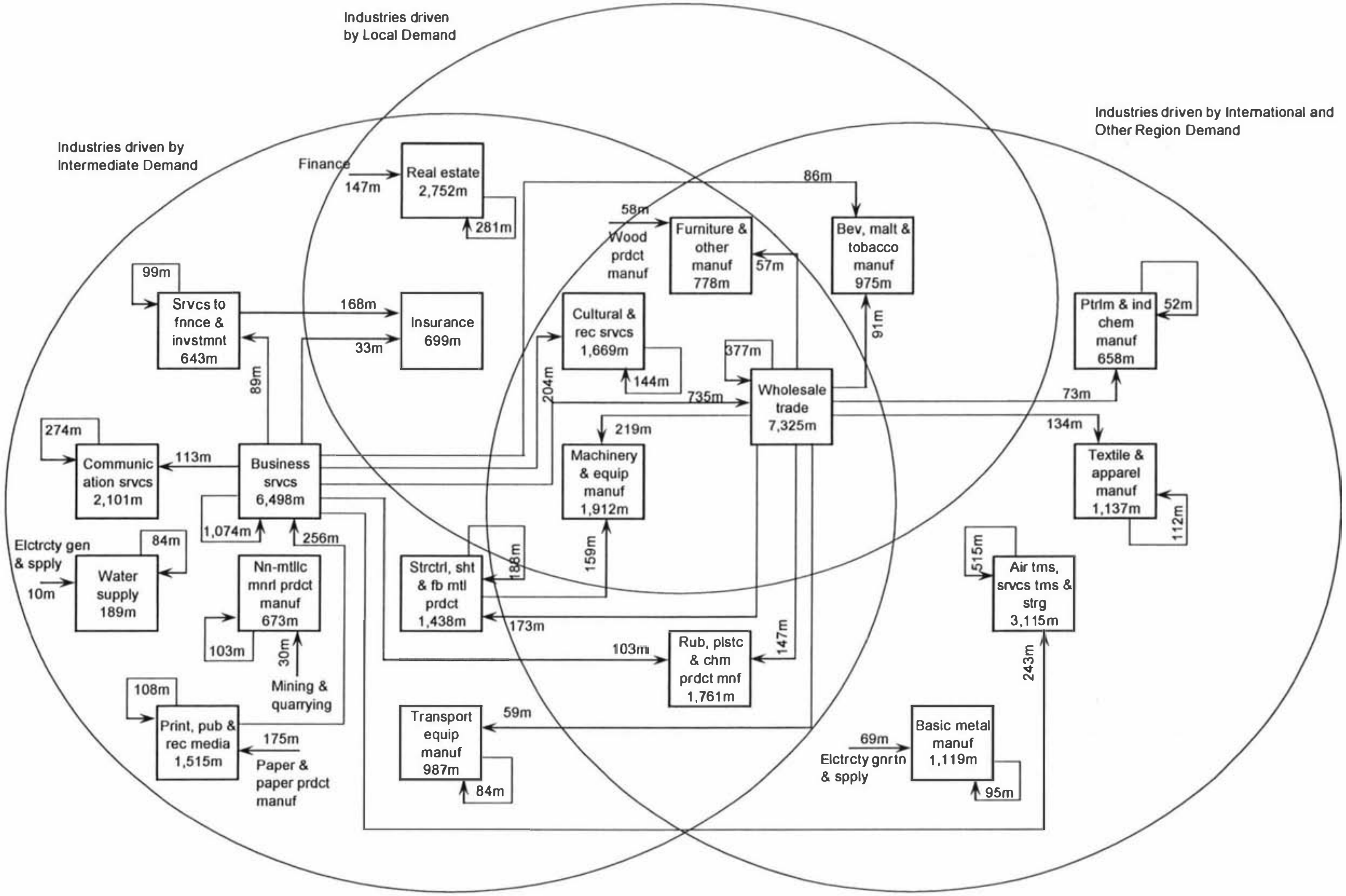

Figure 5.3 Auckland Region's Clusters of Comparative Advantage, 1997-98

5.2.5.1 Industries Driven by Export Demand

A feature of the industries driven by export demand is that, with the exception of Air transport and storage [35] and Wholesale trade [30], they are all involved in manufacturing. Furthermore, the emphasis is primarily on light manufacturing such as Beverages, malt and tobacco [13]; Textile and apparel [14]; Rubber, plastics and chemical products [19]; and Furniture and other manufacturing [25]. Basic metal manufacture [21], primarily steel manufacture at Glenbrook, is the exception. Glenbrook produces steel using titanomagnetite sand as an ore and low quality coal as the redundant. It can produce around 700,000 tonnes per annum, half of which is generally exported, with the remainder satisfying about half New Zealand's steel requirements (Statistics New Zealand, 1999b).

There are no major interdependencies highlighted between the light manufacturing industries driven by export demand. It is however important to note that the Wholesale trade [30] industry plays a critical role in the distribution of commodities between these industries. Approximately three-quarters (73.8 percent) of the Wholesale trade industry's inputs[155] are sourced from intermediate demand industries, with the remainder from international and interregional imports. Thus, the Wholesale trade industry acts as the key distributor of domestically produced light manufacturing commodities within the Auckland Region economy.

The input mixes of the light manufacturing industries with comparative advantage reveal two distinct groupings. On the one hand, the input mixes of the Textile and apparel [14] and Furniture and other manufacturing [25] industries depend upon significant inputs of primary products sourced from other regions in New Zealand. On the other hand, the input mixes of the Beverage, malt and tobacco [13] and Rubber, plastic and chemical product [19] manufacturing industries largely depend on products sourced from other industries within the Auckland Region economy.

Air transport and its associated services [35] is also identified as a key industry driven by export demand. Auckland International Airport is the country's main gateway handling the bulk of airfreighted exports. More than 7.5 million domestic and international passengers arrived and departed through Auckland airport for the year ending June 1997, a figure almost twice the then resident population of New Zealand. Auckland International Airport is a critical factor in the strength of businesses and their associated financial services. Of the top 200 largest companies in New Zealand, an estimated 96 companies had their head offices situated in Auckland Region,

[155] Not including primary inputs such as wages and salaries, subsidies, depreciation of fixed capital and so on.

at least in partly because of Auckland International Airport (Deloitte and Touche Consulting Group, 1997).

5.2.5.2 Support Industries Driven by Intermediate Demand

Two key clusters of comparative advantage are apparent among industries driven by intermediate demand in Auckland Region, namely provision of Business services [42] and Wholesale trade [30]. Business services [42] are provided to industries driven by both local and export demand, as well as to the region's financial and insurance industries. Only 14 percent of Business services [42] outputs are provided to comparative advantage industries driven purely by intermediate demand. All of these industries are also service industries e.g. Services to finance and investment [39] and Communication services [36]. This is not surprising as, relative to the national economy, business and financial services provide a larger proportion of jobs, a finding aligned with Auckland Region's importance as a commercial hub. The remaining Business services [42] outputs are to industries driven by some combination of intermediate, local or export demand, and are utilised by service industries (e.g. Cultural and recreational services [47]) and light manufacturing industries (e.g. Rubber, plastic and chemical manufacturing [19]). Another industry with comparative advantage is Printing, publishing and recorded media [17] which provides large inputs into the Business services [42] industry. The fastest growing areas of the Auckland Region economy over the past decade have been finance, real estate and business services, all of which appear as industries with comparative advantage in the Auckland Region (Auckland Regional Council, 2003, 2004).

Another area that has experienced growth is the distribution sector with Wholesale trade [30] playing a pivotal role in servicing light manufacturing industries, in particular Machinery and other equipment [24], Transport equipment [23], Structural, sheet and fabricated metal [22], Rubber, plastic and chemical [19] and Furniture and other [25] manufacturing. The manufacturing industry, although historically significant to the Auckland Region economy, has declined in relative importance in recent years, with a move towards import substitution. The central role of Wholesale trade [30] in servicing light manufacturing highlights this emphasis on processing, repackaging and redistribution of commodities.

5.2.5.3 Service Industries Driven by Local Demand

Within Auckland Region, no industries with a comparative advantage are driven purely by local demand. In fact, education, health or community, social or personal industries are notably absent as drivers of local demand. The under representation of these industries in Auckland

Region as compared to the nation may be more a factor of economies of scale or the ability to provide such services in a more spatially centralised way than in other regions in New Zealand. A particularly notable exception is the absence of education as driven by both local and international demand, although this industry has grown substantially since the 1997-98 static snapshot analysed here.

Nevertheless, several industries are driven by either a combination of local, interregional and international demand (e.g. Beverage, malt and tobacco manufacturing [13], Furniture and other manufacturing [25], and Wholesale trade [30]), a combination of local and intermediate demand (e.g. Real estate [40] and Insurance [38]) or a combination of local, export and intermediate demand (e.g. Furniture and other manufacturing [25] and Wholesale trade [30]).

5.2.6 Multiplier Analysis of Income and Employment Impacts

Perhaps the major reason for deriving industry-by-industry model from their commodity-by-industry model is that conventional input-output multipliers may be calculated. Input-output multipliers show the relationship between an additional unit of spending (final demand) and changes in output, income, value added and employment within the economy. They capture not only the *direct* effects of additional spending captured, but also the *indirect* effects resulting from the interdependencies that exist between industries within the economy. Say, for example, a group of investors decide to invest in the development of a high-rise tower block. The major direct impacts resulting from this investment would primarily be felt within the construction industry e.g. payments by developers for architectural services, project managers, earthworks, carpentry services and so on. In turn, this would affect associated expenditure, e.g. purchases of steel, concrete and timber from other industries. In this way, economic impacts beyond the initial change in final demand may be initiated in the economy. Moreover, additional impact may be *induced* through household expenditure generated because more people earn wages and salaries. Input-output practitioners summarise direct and indirect economic impact using Type I multipliers, and direct, indirect and induced economic impact using Type II multipliers.

Although input-output multipliers are not a modern development, having been first conceived of by Kahn (1931) and popularised by Keynes (1936), they are a useful measure of structural interdependence within an economy. Moreover, they are not only used below to summarise the structural financial interdependencies of the Auckland Region economy in terms of economy output, income, value added and employment, but when coupled with the physical equivalents outlined in Chapter 6, are also used to construct new measures of the impact of structural interdependence. The calculation of output, income, value added and employment multipliers is described in detail in Appendix G.

5.2.6.1 Output Multipliers

Output multipliers relate a unit of spending to an increase in output in the economy. Industries with large Type I output multipliers in the Auckland Region (Table 5.4) included Water supply [28], Construction [29], Structural, sheet and fabricated metal product manufacture [22] and Machinery and equipment manufacture [24]. These results corroborate existing research findings; for example, the Auckland Regional Council (2003, 2004) estimates that construction, particularly residential housing growth fuelled by an increasing population, was responsible for more than 30 percent of Auckland Region's economic growth during the past decade. The strong linkage between Structural, sheet and fabricated metal product [22] and Machinery and equipment [24] manufacturing is aligned to the construction industry and the presence of the nationally significant Glenbrook steel mill. The provision of reticulated water is a critical operational ingredient in many manufacturing industries; this was critically highlighted during the region's 1994 water crises,[156] and acted as a catalyst for constructing the Waikato pipeline. By contrast, the Finance [7] and Education [45] industries exhibit very weak interlinkages within the region's economy. Since the mid 1990s, Auckland Region has witnessed considerable growth in 'export-education' (i.e. foreign student registrations) spurred by favourable foreign exchange rates and international perceptions of New Zealand as a politically stable, clean-green, and safe place to live. While only minimal indirect effects will be stimulated by education expenditure, more significant economic impact will be generated through foreign student expenditure or Retail trade [31] and Personal and other community services [48].

[156] At the time the New Zealand Treasury speculated that the drought would cost $800 million in real terms (National Business Review, 1994).

Table 5.4 Output Multipliers for Auckland Region and New Zealand, 1997-98

	Auckland Region				New Zealand	
	Type I Output Multiplier	Type II Output Multiplier	Type I Output Multiplier Rank	Type II Output Multiplier Rank	Type I Output Multiplier Rank	Type II Output Multiplier Rank
1 Hort & fruit growing	1.59	2.44	31	27	18	12
2 Livestock & cropping	1.54	2.21	36	34	13	16
3 Dairy cattle farming	1.48	2.05	41	42	33	40
4 Other farming	1.65	2.21	24	35	22	33
5 Srvcs to ag, hnt & trppng	1.62	2.52	27	21	23	15
6 Forestry & logging	1.53	1.95	38	45	26	38
7 Fishing	1.35	1.81	48	46	42	46
8 Mining & Quarrying	1.57	2.18	33	37	21	31
9 Oil & gas explr & extrc	1.60	2.07	30	41	20	39
10 Meat & meat prdct manuf	1.58	2.19	32	36	3	1
11 Dairy prdct manuf	1.36	1.64	46	47	2	4
12 Other food manuf	1.83	2.55	7	18	9	20
13 Bev, malt & tobacco manuf	1.92	2.57	5	17	8	25
14 Textile & apparel manuf	1.64	2.42	25	28	11	11
15 Wood prdct manuf	1.60	2.28	29	31	4	5
16 Paper & paper prdct manuf	1.53	2.12	37	38	36	41
17 Print, pub & rec media	1.71	2.60	16	16	30	30
18 Ptrlm & ind chem manuf	1.76	2.39	12	30	34	43
19 Rub, plstc & chm prdct mnf	1.67	2.40	22	29	32	35
20 Nn-mtllc mnrl prdct manuf	1.76	2.51	13	22	17	22
21 Basic metal manuf	1.83	2.50	6	23	7	14
22 Strctrl, sht & fb mtl prdct	1.96	2.89	3	5	10	10
23 Transport equip manuf	1.71	2.45	17	25	35	36
24 Machinery & equip manuf	1.93	2.80	4	8	16	18
25 Furniture & other manuf	1.76	2.69	14	12	14	9
26 Elctrcty gnrtn & spply	1.68	2.10	21	40	5	27
27 Gas supply	1.54	2.01	35	43	12	32
28 Water supply	2.34	2.90	1	4	1	6
29 Construction	1.98	2.87	2	6	6	7
30 Wholesale trade	1.69	2.53	20	20	24	26
31 Retail trade	1.60	2.67	28	13	38	24
32 Accom, restaurants & bars	1.77	2.62	11	15	15	13
33 Road transport	1.71	2.72	18	11	31	23
34 Water & rail trans	1.36	2.21	45	33	44	42
35 Air trns, srvcs trns & strg	1.66	2.44	23	26	37	37
36 Communication srvcs	1.49	2.12	40	39	43	45
37 Finance	1.37	2.22	44	32	48	44
38 Insurance	1.64	2.49	26	24	40	34
39 Srvcs to fnnce & invstmnt	1.81	2.81	9	7	27	21
40 Real estate	1.52	1.96	39	44	41	47
41 Ownership OOD	1.39	1.59	43	48	46	48
42 Business srvcs	1.76	2.78	15	10	29	19
43 Central government	1.55	3.19	34	1	39	2
44 Local government	1.82	3.02	8	2	19	3
45 Education	1.35	2.80	47	9	47	17
46 Health & community srvcs	1.45	2.63	42	14	45	29
47 Cultural & rec srvcs	1.70	2.55	19	19	28	28
48 Personal & other comm srvcs	1.81	2.99	10	3	25	8

Once induced impacts, initiated through consumer spending, are considered (as recorded by Type II multipliers), the ranking of industries which are most strongly interconnected in the economy changes. Both Central [43] and Local [44] government display a high level of interdependence within the regional economy. Since the fourth Labour Government in 1984, central government policy has focused on economic deregulation, breaking of trade tariffs and, in the case of sub-national governance, devolution to local authorities. Nevertheless, lack of leadership and direction at the national level on major issues within Auckland Region (e.g. traffic congestion, energy and water supply) has led to more interventionist policy since the mid 1990s e.g. the appointment of a minister to assist the Prime Minister with Auckland Region issues, the diversion of national petrol taxes revenue to help alleviate Auckland Region's roading issues, and the legislation of the Waikato Pipeline Act. At the local government level, significant effort has been devoted in recent years to an Auckland-wide growth policy (e.g. the Growth Forum, the Auckland Regional Land Transport Strategy (ARLTS), and Regional Economic Development Strategy (AREDS)) and infrastructure funding and planning (e.g. the establishment of Infrastructure Auckland, and its successors Auckland Regional Holdings (ARH) and Auckland Regional Transport Authority (ARTA)). Thus, taken together, central and local government have a significant effect on interlinkages within the Auckland Region economy, not only in terms of expenditure patterns (as captured by multipliers), but also through the circumlocutory effects of policy.

5.2.6.2 Value Added Multipliers

Value added multipliers show the relationship between an additional unit of spending and changes in the level of value added generated in an economy. Underpinning these value added multipliers is the argument that if an industry's output changes, there will be an associated change in value added and, in turn, final demand. Value added multipliers for Auckland Region are shown in Table 5.5. Industries are ranked according to multiplier size in a descending order. Columns 5 and 6 of the Table records each industry's equivalent rank in the national economy e.g. the Auckland Region Water supply [28] industry value added multiplier ranks as the third largest multiplier regionally, while nationally the Water supply industry ranks fourth.

The rank ordering of the five largest Type I and Type II value added industry multipliers reveals similar rankings across industries, irrespective of the introduction of induced effects. These industries include the Beverage, malt and tobacco industry [13] which has historically been a dominant local industry (Statistics New Zealand, 1999b), and Machinery and equipment manufacture [24] which delivers and consumes the outputs of the region's light manufacturing industries.

Low ranking industries in terms of value added flow-on effects include Real estate [40], Finance [37], Education [45] and Ownership of owner occupied dwellings [41]. In this respect, Auckland Region is similar to the nation. The flow on impacts of these industries tend to be low because these industries have low operating overheads and limited interconnections with manufacturing and primary industries.

Table 5.5 Value Added Multipliers for Auckland Region and New Zealand, 1997-98

	Auckland Region				New Zealand	
	Type I Value Added Multiplier	Type II Value Added Multiplier	Type I Value Added Multiplier Rank	Type II Value Added Multiplier Rank	Type I Value Added Multiplier Rank	Type II Value Added Multiplier Rank
1 Hort & fruit growing	1.51	1.90	36	36	26	26
2 Livestock & cropping	1.46	1.76	40	40	27	33
3 Dairy cattle farming	1.60	1.99	32	34	25	27
4 Other farming	1.82	2.20	16	25	18	19
5 Srvcs to ag, hnt & trppng	1.58	2.03	35	32	30	29
6 Forestry & logging	2.96	3.73	2	2	5	5
7 Fishing	1.40	1.69	42	43	38	41
8 Mining & Quarrying	1.59	1.95	34	35	23	28
9 Oil & gas explr & extrc	1.91	2.34	13	15	15	17
10 Meat & meat prdct manuf	1.97	2.54	11	10	2	2
11 Dairy prdct manuf	1.79	2.17	19	28	1	1
12 Other food manuf	2.21	2.83	5	5	7	7
13 Bev, malt & tobacco manuf	3.00	3.81	1	1	3	3
14 Textile & apparel manuf	1.77	2.30	21	18	12	11
15 Wood prdct manuf	1.74	2.24	25	23	9	9
16 Paper & paper prdct manuf	1.62	2.03	31	31	31	32
17 Print, pub & rec media	1.68	2.16	30	29	33	35
18 Ptrlm & ind chem manuf	2.02	2.50	10	11	14	16
19 Rub, plstc & chm prdct mnf	1.81	2.31	17	16	29	25
20 Nn-mtllc mnrl prdct manuf	1.92	2.44	12	13	16	15
21 Basic metal manuf	2.08	2.60	8	9	8	10
22 Strctrl, sht & fb mtl prdct	2.04	2.65	9	7	17	14
23 Transport equip manuf	1.90	2.46	14	12	22	22
24 Machinery & equip manuf	2.22	2.89	4	4	13	12
25 Furniture & other manuf	1.74	2.26	26	21	21	18
26 Elctrcty gnrtn & spply	2.13	2.61	7	8	6	6
27 Gas supply	1.75	2.13	24	30	11	13
28 Water supply	2.79	3.45	3	3	4	4
29 Construction	2.18	2.83	6	6	10	8
30 Wholesale trade	1.78	2.29	20	19	19	21
31 Retail trade	1.43	1.85	41	38	41	39
32 Accom, restaurants & bars	1.75	2.27	23	20	20	20
33 Road transport	1.59	1.99	33	33	37	37
34 Water & rail trans	1.29	1.65	46	46	44	43
35 Air trns, srvcs trns & strg	1.76	2.25	22	22	32	30
36 Communication srvcs	1.51	1.88	37	37	40	40
37 Finance	1.30	1.66	45	45	47	46
38 Insurance	1.70	2.18	28	27	36	36
39 Srvcs to fnnce & invstmnt	1.84	2.37	15	14	28	24
40 Real estate	1.47	1.68	39	44	42	45
41 Ownership OOD	1.39	1.50	43	48	43	48
42 Business srvcs	1.72	2.22	27	24	34	34
43 Central government	1.27	1.69	47	42	45	42
44 Local government	1.47	1.85	38	39	39	38
45 Education	1.17	1.53	48	47	48	47
46 Health & community srvcs	1.33	1.75	44	41	46	44
47 Cultural & rec srvcs	1.80	2.31	18	17	24	23
48 Personal & other comm srvcs	1.69	2.20	29	26	35	31

5.2.6.3 Employment Multipliers

Employment multipliers show the relationship between an additional unit of spending and changes in the level of employment in an economy. Employment multipliers for the Auckland Region are depicted in Table 5.6, using the same layout as Table 5.5.

Industries with large Type I and Type II employment multipliers in the Auckland Region include Oil and gas exploration [9], Beverage, malt and tobacco manufacture [13], Forestry and logging [6] and the Electricity generation [26] and Water supply [28] utilities. By comparison, these industries are ranked, respectively, first, third, tenth, fourth and seventh at the national level. These similarities in the rankings of the employment multipliers at the regional and national levels are not unexpected. Commentators such as the Auckland Regional Council (2003, 2004) argue that the region's business cycle closely resembles the nation's, while others simply note that, with the exception of farming activities, Auckland Region is the dominant manufacturing and service hub in New Zealand.

Several similarities exist between the industries with large employment multipliers within the Auckland Region. The most obvious similarity is that they are primarily utilities or manufacturing industries with significant backward linkages or upstream effects associated with their operation, typically these linkages are to primary resource extraction industries e.g. water and beverage manufacture. A second similarity is that it is principally the management structures of the industries that are located within Auckland Region, and these management structures are purchasing manufactured goods (particularly machinery and equipment) that are mostly imported, finished and redistributed from Auckland Region. A final similarity is that these industries have typically been the mainstay of the Auckland Region economy.

Table 5.6 Employment Multipliers for Auckland Region and New Zealand 1997-98

	Auckland Region				New Zealand	
	Type I Employment Multiplier	Type II Employment Multiplier	Type I Employment Multiplier Rank	Type II Employment Multiplier Rank	Type I Employment Multiplier Rank	Type II Employment Multiplier Rank
1 Hort & fruit growing	1.27	1.46	45	45	41	43
2 Livestock & cropping	1.38	1.61	40	40	28	36
3 Dairy cattle farming	1.35	1.55	42	42	38	42
4 Other farming	1.46	1.67	38	39	34	39
5 Srvcs to ag, hnt & trppng	1.35	1.59	41	41	40	41
6 Forestry & logging	3.31	4.13	3	5	9	10
7 Fishing	1.47	1.79	37	38	36	38
8 Mining & Quarrying	2.22	2.95	11	11	11	11
9 Oil & gas explr & extrc	7.30	10.04	1	1	1	1
10 Meat & meat prdct manuf	1.92	2.40	19	20	6	6
11 Dairy prdct manuf	2.80	3.48	8	9	2	2
12 Other food manuf	2.22	2.80	12	12	12	13
13 Bev, malt & tobacco manuf	4.25	5.45	2	2	3	3
14 Textile & apparel manuf	1.62	2.01	30	32	17	20
15 Wood prdct manuf	1.61	2.00	31	33	15	16
16 Paper & paper prdct manuf	1.96	2.63	16	15	16	15
17 Print, pub & rec media	1.65	2.13	28	28	31	29
18 Ptrlm & ind chem manuf	2.82	3.70	7	7	8	8
19 Rub, plstc & chm prdct mnf	1.94	2.52	17	17	21	19
20 Nn-mtllc mnrl prdct manuf	2.09	2.74	13	13	14	14
21 Basic metal manuf	2.72	3.59	9	8	10	9
22 Strctrl, sht & fb mtl prdct	1.89	2.39	22	21	22	22
23 Transport equip manuf	1.89	2.38	21	22	24	25
24 Machinery & equip manuf	2.00	2.51	15	18	19	21
25 Furniture & other manuf	1.56	1.94	33	35	30	32
26 Elctrcty gnrtn & spply	3.29	4.35	4	3	4	4
27 Gas supply	3.00	4.15	6	4	5	5
28 Water supply	3.09	3.95	5	6	7	7
29 Construction	1.89	2.31	20	23	20	23
30 Wholesale trade	1.71	2.15	26	27	25	26
31 Retail trade	1.28	1.54	43	43	45	44
32 Accom, restaurants & bars	1.28	1.45	44	46	44	45
33 Road transport	1.61	1.99	32	34	35	37
34 Water & rail trans	1.48	2.10	35	29	37	28
35 Air trns, srvcs trns & strg	2.02	2.67	14	14	18	17
36 Communication srvcs	1.69	2.16	27	25	32	30
37 Finance	1.48	2.04	36	31	43	34
38 Insurance	1.93	2.57	18	16	23	18
39 Srvcs to fnnce & invstmnt	1.87	2.41	23	19	26	24
40 Real estate	1.81	2.21	24	24	27	27
41 Ownership OOD	0.00	0.00	48	48	48	48
42 Business srvcs	1.64	2.06	29	30	33	35
43 Central government	1.39	1.93	39	36	42	33
44 Local government	2.36	3.29	10	10	13	12
45 Education	1.15	1.43	47	47	47	47
46 Health & community srvcs	1.25	1.53	46	44	46	46
47 Cultural & rec srvcs	1.73	2.16	25	26	29	31
48 Personal & other comm srvcs	1.50	1.83	34	37	39	40

5.2.6.4 A Final Note on Auckland Region's Structural Interdependencies

To complete the analysis of Auckland Region's multiplier impacts two further insights, albeit less related to the core theme of multipliers, require additional discussion. Firstly, structural interdependencies in the Auckland Region economy have weakened over time. Work by Le Heron and McDonald (2005) has replicated the clusters of comparative advantage analysis, undertaken in Section 5.4.5, and the multiplier analysis work performed here, for the 1986-87, 1989-90, 1992-93, 1995-96, 1997-98, and 2000-01 financial years. Although the principal theme of this comparative static study is identification and explanation of Auckland Region's drivers of structural change, the paper shows that interlinkages within the region's economy have been weakening in favour of a more open Pacific-based economy. Supporting this argument is an increased gap between the region's import dependence and GRP growth i.e. regional imports are growing at a greater rate than regional GRP.

Secondly, the impact of tourism on the Auckland Region economy is apparently ignored. This is surprising given that the tourism industry has grown substantially over the last two decades (McDermott, 1998; Goh and Fairgray, 1999a, 1999b; Statistics New Zealand, 2000), and that Auckland Region is the key gateway in and out of the nation. The apparent omission of tourism effects is however more an artefact of industry (ANZSIC) classification than actual occurrence. This reveals a significant limitation of the way statistics are collected in New Zealand, namely, the impacts of tourism are ostensibly omitted because coding by the ANZSIC system which has no tourism industry *per se*, but instead represents tourism through the partial output of several industries, e.g. Retail trade [31], Accommodation, restaurants and bars [32], Air transport and and associated services [35]. This definitional problem is not limited to tourism alone; other emerging industries are also not recorded uniquely e.g. the amalgamation of telecommunications, radio and television. Ideally, with these emerging industries typically focused on consumption rather than production, an aligned movement in the way industries are classified seems compelling.

Chapter Six

Physical Input-Output Model: Physical Flows in the Auckland Region Economy and Environment

In this Chapter a physical input-output model[157] of the Auckland Region economy is constructed, using the commodity-by-industry framework (Table 4.2) as was previously mathematically defined in Chapter 4. To the author's knowledge, this is the first *regional-level* physical input-output model that has been constructed, with previous efforts focusing on the national level.[158] The most comprehensive models developed, for example, are for Germany and Denmark, both of which are at the national level.

This model has two features that can be considered to be extensions to the economic input-output model: (1) it quantifies the flow of commodities between industries in the Auckland Region economy in physical (mass[159]) terms rather than in financial terms, and (2) it quantifies the physical flows between industries in the economy and the biophysical environment. This includes mainly raw material inputs (e.g. soil, water, air) used by economic industries and residuals (e.g. solid wastes, air emissions) produced by these industries.

The construction of physical input-output models is important for understanding the *biophysical functioning* of the economy, in terms of theoretical schemas advocated by the early ecological economists such as Boulding (1966), Georgescu-Roegen (1971) and Daly (1973), which emphasised the criticality of energy and mass flows in sustaining the economy. Without such an analytical tool, it is difficult to determine how the economy is performing in physical sustainability terms, e.g. how much waste is being recycled, how industries directly and

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[157] The term PIOT (Physical Input-Output Table) is often used in the literature. In this Chapter, the author prefers to use the term physical input-output model or matrix for the reason stated in Chapter 4. Although the description in this Chapter relies on the specification and manipulation of matrices, these can be directly converted to an equation-based model (e.g. for the type of multiplier analysis carried out in Section 6.3). For this reason primarily, the author has tended to refer to a physical input-output model rather than matrix.

[158] Several other nations have developed economy wide material flow accounts (see, for example, Adriaanse *et.al.* (1997) and Steurer and Schütz (2000)), national resource accounts (e.g. France, Norway and Canada), SEEA accounts or MIPS/Factor 10-type (Schmidt-Bleek, 1994a, 1994b, 1994c, 1997) analyses. These approaches are however not considered comprehensive in the context of this thesis, as they tend to focus on either the economy as an aggregate, or on selected industries within the economy. This differs from the framework utilised here which comprehensively evaluates, on an industry-by-industry basis, physical flows.

[159] The physical flows are measured in mass (tonnes), even for energy resources such as coal. This was done in order to be consistent with other PIOT research. Data on energy inputs and land inputs are also collected in this exercise although will not be reported in this Chapter – refer to Appendix K. This latter data (energy, land) is important in understanding the biophysical functioning of the economy and was used in the calculation of Auckland Region's ecological footprint in Chapter 8.

indirectly depend on fossil fuel inputs, what the critical connectivity's in the economy are in mass and energy terms, and so forth. Furthermore, because Chapter 6 focuses on an urban region, the model can be seen to be the first operationalisation of the type of city-level physical input-output model first proposed by Geddes (1885) in which he imagined energy and material flows through cities could be depicted and quantified.

The structure of the physical input-output model is similar but not the same as the German model developed by Stahmer *et al.* (1996, 1997, 1998). Most notably the model presented in this Chapter of the thesis differs from the German model in that: (1) a 'materials balance' column is added, and (2) to ensure direct comparability with the economic input-output model, some raw materials that have a market price (e.g. coal), are classified as commodities rather than raw materials as in the German model.

6.1 Generation of an Auckland Region Physical Input-Output Model

The methodology used to construct the New Zealand and Auckland Region physical input-output model builds on the input-output accounting framework conceptualised in Chapter 4 and constructed in financial terms in Chapter 5. The same industry and commodity definitions are employed so that comparisons can be made between the results of the financial and the physical input-output models. The physical input-output model is initially constructed for New Zealand using a combination of data from the financial input-output model, commodity prices, and the insertion of superior *ad hoc* data. Development of the Auckland Region physical input-output model is based on the prices established in the construction of the national input-output model, supplemented where possible with region specific *ad hoc* data. With limited access to national statistical agency data, the New Zealand and Auckland Region physical input-output models can be considered to be only tentative prototypes.

A significant amount of research funding has been granted by the Foundation of Science, Research and Technology (FoRST), the New Zealand Government's principal science funder, to improve the physical flow estimates presented here at both the national and regional level. The national work falls under the 'Ecological Footprint Plus' Programme (WROX0305), while the regional work falls under the 'Sustainable Pathways' Programme (MAUX0306). These projects consist of representatives from several governmental research institutes and private sector companies within New Zealand, including the New Zealand Centre of Ecological Economics, Landcare Research Ltd, Canesis Network Ltd, Forestry Research Institute Ltd, Massey University, WelNetworks Ltd, Market Economics Ltd and various others. Researchers from these organisations will provide superior data, verify existing calculations, and expand the number of commodities evaluated within the framework.

6.1.1 Methodological Process in the Auckland Region Study

In this Section a methodology is developed that generates the within economy physical flow matrices for New Zealand and, in turn, for Auckland Region (i.e. matrices $\widetilde{\mathbf{S}}$, $\widetilde{\mathbf{T}}$, $\widetilde{\mathbf{U}}$, $\widetilde{\mathbf{V}}$, $\widetilde{\mathbf{X}}$ and $\widetilde{\mathbf{Y}}$ of Table 4.2). The methodological process consists of a series of 9 steps (Figure 6.1). In steps 1 to 4, the national financial supply-use matrices constructed in Chapter 5 are transformed into the physical input-output model using prices generated from trade statistics. In step 5, superior data from *ad hoc* sources including Statistics New Zealand, producer boards, published industry reports, industry representatives, and so on is inserted. Calculation of service industry physical flow in step 6 completes construction of the prototype New Zealand physical input-output model. Transformation from the nation to Auckland Region is performed in steps 7 and 8. In step 9 industry and commodity definitions are aggregated to facilitate analytical manipulation and reporting.

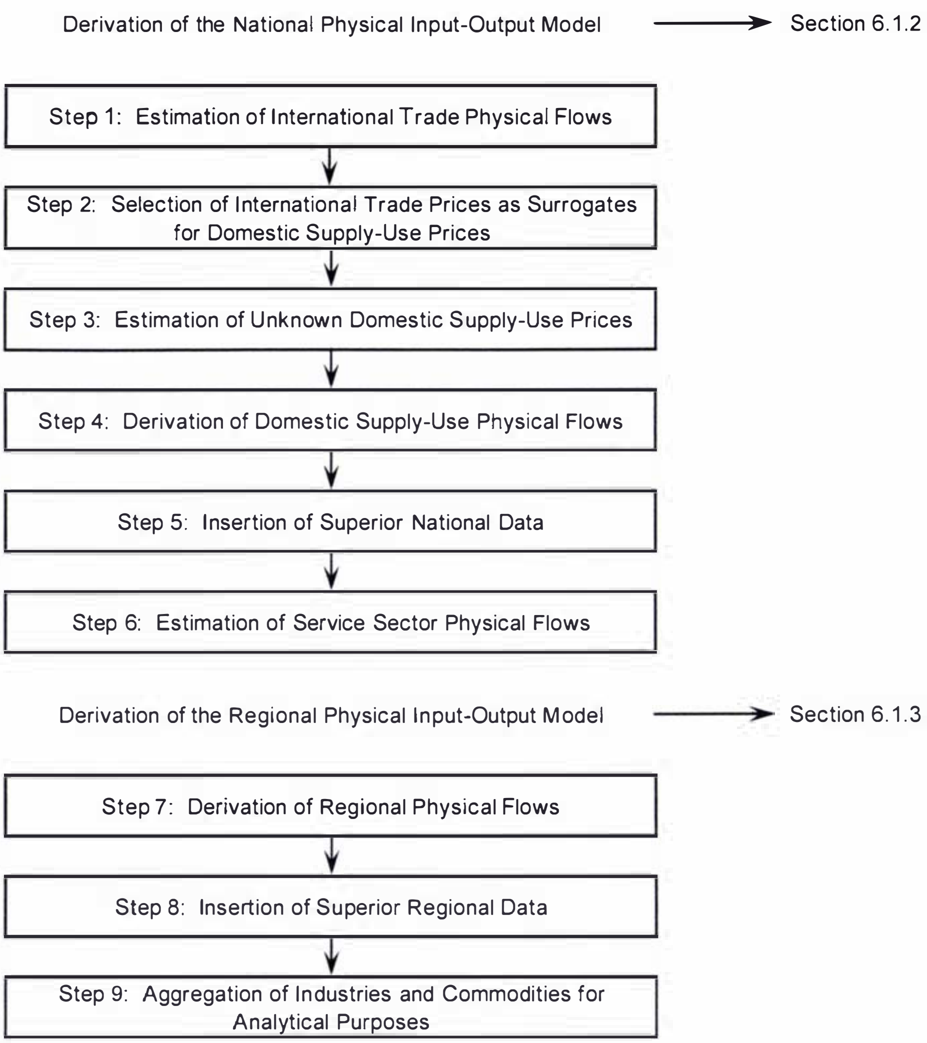

Figure 6.1 Methodological Process for Deriving New Zealand and Auckland Region Physical Input-Output Models

6.1.2 Derivation of a National Physical Input-Output Model

Step 1 Estimation of International Trade Physical Flows

The conversion of financial flows of internationally traded commodities in the New Zealand economy to physical equivalents was undertaken using prices expressed in tonnes[160] per NZ 1998 $ as obtained from Statistics New Zealand's Harmonised System Classification (NZHSC) 1996. The NZHSC 1996 is a subset of the internationally recognised Harmonised System Commodity Description and Coding System. The HSC facilitates statistical and administrative comparability of trade information between nations. Traded commodities are classified under approximately 5,000 headings in a broad 6-digit structure. The NZHSC disaggregates this structure to a 10-digit level comprising just over 13,000 commodity groups. The following

[160] These are tonnes in net weight terms, i.e. without packaging. All further occurrences of the word 'tonne' in this Chapter represent 'net weight tonnes' – unless stated otherwise.

information for each NZHSC code is available: (1) formal descriptor; (2) estimated financial value in New Zealand dollars, with exports valued free on board (fob - the value of goods in New Zealand ports before export) and imports valued in both value for duty (vfd) and cost including insurance and freight (cif)[161]; (3) gross weight[162], and (4) net weight or counts.

Prices per tonne were calculated for both imports and exports for approximately 130 out of the 210 commodity definitions of the commodity-by-industry accounting framework.[163] This required aggregating net weights and traded values (with imports measured cif[164] and exports fob) of the NZHSC 10-digit commodity groupings to a 5-digit level. These, in turn, were matched to the 130 commodities of the commodity-by-industry accounting framework based on a concordance supplied by Statistics New Zealand. Export prices, $\widehat{px}_i$, expressed in net weight tonnes per NZ 1998 \$, were calculated as

$$\widehat{\mathbf{px}}=\mathbf{Xi}/\widetilde{\mathbf{X}}\mathbf{i}\,,\ \widetilde{\mathbf{X}}\mathbf{i}\neq 0\,, \tag{6.1}$$

and import prices, $\widehat{py}_j$, in net weight tonnes per NZ 1998 \$, as

$$\widehat{\mathbf{py}}=\mathbf{i'Y}/\mathbf{i'}\widetilde{\mathbf{Y}}\,,\ \widetilde{\mathbf{i'Y}}\neq \mathbf{0}. \tag{6.2}$$

Step 2 Selection of International Trade Prices as Surrogates for Domestic Supply-Use Prices

Once import and export prices per tonne had been established for the 130 commodities, it was then possible to derive estimates of physical mass for each commodity group. This was achieved by assuming price invariance between traded and domestic commodities, i.e. import/export commodity prices per net weight tonne were used as surrogates for their domestic supply/use counterparts. The international export price per tonne for pipfruit, for example, was used as a surrogate for its domestic use equivalent. The implicit assumption of equivalence however requires additional thought.

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[161] These values are converted from foreign currency when import documents are processed by the New Zealand Customs service. The exchange rates used are set by the New Zealand Customs Service on a fortnightly basis.

[162] Gross weight includes cargo and packaging, but excludes the weight of re-usable cargo containers.

[163] The remaining 80 commodity definitions relate predominantly to the provision of services – the physical flows of which are negligible. Furthermore, the physical flows associated with these services may be computed indirectly from their physical inputs (refer to step 5).

[164] Imports were measured in cif rather than vfd terms as it is argued that cif costs would need to be equal to, or less than, domestic costs to provide an overseas supplier with sufficient incentive to import goods into New Zealand.

Question 1: What justifications exist for assuming equivalence between a trade price and a domestic equivalent? Consider, for example, an importer and a domestic supplier producing a competing commodity. Under perfect market conditions, where all other things remain equal, competition between the price paid for an imported/exported commodity and the price paid for the same commodity supplied/used domestically, would exhibit one of the following relationships:

- *Import price per tonne > domestic supply price per tonne.* Consumers of the commodity will purchase it from the domestic supplier rather than from the importer. If the importer is to be competitive a reduction in the price to at least the domestic supply price will be necessary.
- *Import price per tonne < domestic supply price per tonne.* Consumers of the commodity will purchase it from the importer rather than the domestic supplier. If the domestic supplier is to be competitive a reduction in the price to at least the import price will be necessary.
- *Import price per tonne = domestic supply price per tonne.* Both importer and domestic supplier operate without price competition.

Combating a downward spiral in price is critical to the economic survival of both the domestic supplier and importer. If, for example, the importer sets too low a price then they may cease being financially viable and ultimately exit the market. A similar set of behaviours can be established for the competitive relationship between an exporter and domestic use. The relationships outlined here may only arise under perfect market conditions. Markets are however often far from perfect – due at least in part to:

- *Tariffs.* To protect domestic suppliers, many governments place tariffs on incoming commodities from other nations. The highly deregulated nature of the New Zealand economy, where almost all tariffs have been removed from commodity imports, means that this is unlikely to be a significant factor in the relationship between supply and use price. Nevertheless for New Zealand exporters, where markets are controlled by other governments, this will certainly be a significant factor in the setting of price.
- *Seasonality and climate.* Seasonal fluctuations in climate have a significant impact on trade and domestic prices, particularly for primary producers and, through interdependencies, their associated processing industries. Although technological innovation such as refrigeration can minimise the impact of seasonality and climatic fluctuations, some industries remain susceptible to seasonal and climatic influences. In

the context of this thesis, these impacts will be averaged out over a year. Furthermore, the more urban economic profile of Auckland Region means that the impact on local primary producers is not considered to be great, although import substitution by processing/manufacturing may be greatly affected.

- *Business decision making, size and ownership.* Business decisions, such as purchasing commodities while prices are low or in advance through pre-ordering, can result in oscillation around a commodity's optimal price. Similar oscillation may also result from time lags between purchase and use of a commodity. The size of a business may also be a factor in price setting – a substantial bulk-buy may warrant a lower than average price as risk and uncertainty over future price fluctuations can be reduced. Ownership patterns may also affect price as parent industries may purchase from subsidiaries at higher prices simply because of the security of knowing that orders can be filled and production timelines adhered to.

There are also several potentially significant operational weaknesses associated with the price invariance assumption. These are considered below by exploring three further questions:

Question 2: What if exports in a particular commodity grouping exhibit a significantly different mix of sub-commodities than those used domestically?

Differences in the mix of sub-commodities (i.e. at a disaggregation below the 130 commodity groups) between traded and domestic commodities certainly exist. Unfortunately, a paucity of data on domestic commodity consumption and production patterns restricts any analysis of the implications of these differences. Nevertheless, the relationship between NZHSC 5-digit headings and the input-output commodity groups was analysed. Of a possible 128 commodity groups with export prices per tonne only 29 commodity groups were used as surrogates for their domestic use equivalents. Of these 29 commodity groups, one-to-one matches existed in 3 cases (10.3 percent) between NZHSC 5-digit headings and the commodity group definitions, and a further 18 cases (62.1 percent) were dominated (> 50 percent of commodity group financial value) by a single NZHSC 5-digit heading. Similarly, of a possible 126 commodity groups with import prices per tonne, some 61 commodity group prices were used as surrogates for their domestic supply equivalents. Of the 61 commodity groups one-to-one matches existed in 3 cases (4.9 percent) between NZHSC 5-digit headings and commodity group definitions, with a further 24 cases (39.3 percent) being dominated by a single NZHSC 5-digit heading. Overall, these results are considered favourable. Further research is, however, required at the sub-commodity group level on domestic consumption and production patterns to improve these findings.

Question 3: How much of each commodity's output (input) is destined for export (import)?

Generally speaking the greater the contribution made to commodity output by exports, the more likely the domestic use price per tonne will reflect the export price per tonne. In those cases where, say, an export price per tonne for a commodity was used as a surrogate for its domestic use equivalent, the share that exports made up of commodity output, $\tilde{\alpha}$, was calculated (Table 6.1). The Table shows that 14 commodities (48.3 percent of all commodities) were based on surrogate prices per tonne where exports made up 40 percent or more of total commodity output, and 23 commodities (79.3 percent) with 20 percent or more of total commodity output.

Table 6.1 International Exports as a Percentage of Commodity Output, 1997-98

Commodity Group	International Exports as a Percentage of Total Use	Price
	%	$/tonne[1]
18 Other livestock	92.6	73,640
48 Other dairy products	81.9	3,118
49 Prepared fish	78.9	2,648
2 Pipfruit	77.1	1,126
42 Meat and meat products	68.6	3,437
64 Natural textiles	67.9	4,580
72 Tanned skins and leather	67.2	7,653
27 Crustaceans	65.0	22,365
90 Other chemical products	58.6	2,870
3 Kiwifruit	58.2	1,576
24 Other forestry products	48.7	12,354
65 Cotton textiles	48.0	8,046
45 Hides and skins	45.5	7,296
6 Plants, flowers, seeds	40.7	9,374
53 Oils and fats	39.6	927
21 Forestry and logging	35.4	122
47 Yoghurt, buttermilk, icecream	32.1	2,439
89 Industrial chemicals	31.5	273
84 Non metal wastes and scraps	28.2	221
103 Metal wastes	27.5	901
121 Machinery for food production	25.8	15,324
52 Prepared fruit and nuts	25.8	2,100
79 Veneer sheets and plywood	22.7	1,336
70 Carpets	16.6	8,916
7 Raw vegetable materials	14.5	2,902
19 Other animal products	8.7	5,841
80 Builders joinery	8.2	2,509
62 Spirits, wines, beer, tobacco	7.2	1,915
26 Fish	6.5	7,091

Note:
1. Values are 1998 New Zealand dollars.

If an import price per tonne for a commodity was used as a surrogate for its domestic supply equivalent, the share that imports made up of commodity input, $\tilde{\alpha}'$, was estimated (Table 6.2). The Table shows that 34 commodity groups (55.7 percent) were based on surrogate prices where imports made up 40 percent of more of commodity input, and 49 commodity groups (80.3 percent) with 20 percent or more of commodity input.

Table 6.2 International Imports as a Percentage of Commodity Input, 1997-98

Commodity Group	International Imports as a Percentage of Total Supply	Price
	%	$/tonne[1]
13 Unmanufactured tobacco	100.0	6,876
22 Natural gums	100.0	2,900
35 Chemical and fertilizer minerals	100.0	110
126 Audio and video records and tapes	99.1	47,553
12 Beverage and spice crops	95.8	4,303
134 Games and toys	94.8	14,643
110 Engines	88.7	38,782
108 Steam generators	88.0	7,432
113 Ships	85.5	40,125
127 Watches and clocks	84.2	75,932
116 Aircraft and parts	82.0	1,149,852
129 Photographic and scientific equipment	75.6	46,921
124 Computers and parts	75.2	96,084
5 Oil seeds	74.9	1,576
132 Musical instruments	74.3	26,306
68 Woven fabrics	68.2	13,139
120 Machinery for mining	65.5	7,791
66 Man-made fibres and textiles	63.2	4,732
86 Prepared printing plates	62.4	18,601
117 General industrial machinery	61.6	18,123
133 Sports goods	57.0	10,790
76 Footwear	54.5	18,020
75 Handbags and articles of leather	53.7	15,569
95 Pharmaceutical products	52.0	32,399
111 Motor vehicles and parts	51.0	8,599
4 Other fruit and nuts	49.1	1,242
92 Rubber	47.7	4,945
128 Medical equipment	44.2	107,730
115 Other transport equipment	43.6	9,216
123 Office equipment	43.6	29,666
102 Other mineral products	43.3	2,546
98 Pesticides	43.0	10,386
136 Other manufactured articles	42.6	17,796
91 Plastics	42.0	3,013
125 Electric equipment	39.3	26,471
96 Soap and perfumes	36.7	4,879
69 Other textiles	34.5	10,563
99 Glass and glass products	34.4	1,127
131 Jewellery	33.5	1,392,689
74 Clothing	30 9	26,506
112 Coachwork	30.6	5,334
109 Other fabricated metal products	29.2	6,213
119 Agricultural and forestry equipment	28.8	10,197
106 Structural metal products	26.1	1,458
93 Rubber tyres	25.2	4,816
82 Other wood products	25.1	5,765
61 Other food products	24.0	4,743
94 Paints	23.2	7,080
88 Petroleum products	21.4	380
107 Tanks, reservoirs and containers	18.8	5,089
114 Pleasure and sporting boats	15.6	20,383
122 Domestic appliances	14.8	10,590
85 Books and stationery	14.4	13,274
130 Furniture	11.7	5,045
176 Computer software and services	11.0	31,221
81 Wood containers	9.7	8,335
37 Precious metals and stones	9.4	431
71 Twine, rope, netting	9.0	7,689
87 Newspapers and journals	8.8	16,598
135 Prefabricated buildings	8.6	2,717
104 Iron and steel	0.8	757

Note:

1. Values are 1998 New Zealand dollars.

Question 4: Is it reasonable to assume price invariance across all industries that supply or use a commodity?

The use of trade prices per tonne as domestic supply/use surrogates assumes price invariance across all industries either purchasing a commodity, in the case of domestic use, or selling a commodity, in the case of domestic supply. This assumption is, however, certainly incorrect. It is likely, for example, that a company making apple juice concentrate will bulk-buy apples for pulping, at a heavily reduced price, while a local superette (cornershop) will pay a higher premium. In these cases, where the discrepancy is thought to be great, superior data (refer to step 5) should be inserted and prices in the remaining industries adjusted accordingly (refer to steps 3 and 4).

Overall, the trade prices utilised here represent annual average and, as such, price differences between imported and domestic commodities will, to some degree, have been ironed out. Moreover, steps 4 and 8 of the methodological sequence provide significant opportunities for the insertion of superior data to alleviate as many of the discrepancies above as possible.

Step 3 Estimation of Unknown Domestic Supply-Use Prices

Once it was decided whether an international import or export price per tonne would be used to convert domestic supply or use to a physical mass, it was then a matter of algebra to determine the remaining domestic supply or use price per tonne. If, for example, domestic supply had been determined from an export price per tonne then domestic use was algebraically determined so as to ensure that supply and use of a commodity equated, both in financial and physical terms.[165] To compute the unknown domestic supply or use price per tonne using surrogate trade prices per tonne, it is useful to set out the following equations:

$$\widetilde{\widetilde{\mathbf{my}}}=\mathbf{i}'\widetilde{\mathbf{Y}}, \tag{6.3}$$

where $\widetilde{\widetilde{my}}_j$ represents the physical mass of the internationally imported commodity j,

$$\widetilde{\widetilde{\mathbf{mv}}}=\mathbf{i}'\widetilde{\mathbf{V}}, \tag{6.4}$$

[165] Equations 4.9 and 4.10 have previously established that in financial terms the supply of a commodity, α_i, must be equal to the use of that commodity, α_j, where $i=j$. Physical equivalence is similarly established in Equations 4.18 and 4.19.

where $\overparen{\overparen{mv}}_j$ denotes the physical mass of domestically supplied commodity j,

$$\overparen{\overparen{\mathbf{mx}}}=\widetilde{\mathbf{X}}\mathbf{i}\,, \tag{6.5}$$

where $\overparen{\overparen{mx}}_i$ is the physical mass of internationally exported commodity i, and

$$\overparen{\overparen{\mathbf{mu}}} = (\mathbf{U}|\mathbf{S}|\mathbf{T})\mathbf{i}\,, \tag{6.6}$$

where $\overparen{\overparen{mu}}_i$ describes the physical mass of domestically used commodity i.

Together Equations 6.3, 6.4, 6.5 and 6.6 may be used to formulate physical mass balance for commodity i and j, where $i = j$,

$$\overparen{\overparen{my}}_j + \overparen{\overparen{mv}}_j = \overparen{\overparen{mx}}_i + \overparen{\overparen{mu}}_i\,. \tag{6.7}$$

Similarly financial balance (Equation 6.10) may be established with the use of Equations 6.1 and 6.2 and the following two price equations,

$$\overparen{\mathbf{pv}}=\mathbf{i}'(\mathbf{V})/\mathbf{i}'(\widetilde{\mathbf{V}}),\ \ \mathbf{i}'(\widetilde{\mathbf{V}}) \neq 0\,, \tag{6.8}$$

where $\overparen{pv}_j$ is the domestic supply price per tonne for commodity j,

$$\overparen{\mathbf{pu}} = (\mathbf{U}|\mathbf{S}|\mathbf{T})/(\overparen{\mathbf{U}|\mathbf{S}|\mathbf{T}}),\ \ (\overparen{\mathbf{U}|\mathbf{S}|\mathbf{T}}) \neq \mathbf{0}\,, \tag{6.9}$$

where $\overparen{pu}_i$ represents the domestic use price per tonne for commodity j, and

$$\overparen{py}_j\overparen{\overparen{my}}_j + \overparen{pv}_j\overparen{\overparen{mv}}_j = \overparen{px}_i\overparen{\overparen{mx}}_i + \overparen{pu}_i\overparen{\overparen{mu}}_i\,. \tag{6.10}$$

Having established financial and physical mass balance respectively in Equations 6.10 and 6.7, and by substitution of the domestic supply price per tonne for commodity j with its international import equivalent, $\overparen{pv}_j = \overparen{py}_j$, the physical mass of this commodity may be derived,

$$\overset{\frown}{\widetilde{\mathbf{mv}}} = \frac{\mathbf{i'(V)}}{\overset{\frown}{\mathbf{py}}}, \overset{\frown}{\mathbf{py}} \neq 0, \qquad (6.11)$$

as may the domestic use price per tonne for commodity i, $\overset{\frown}{pu}_i$, where i=j,

$$\overset{\frown}{py}_i(\overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j) = \overset{\frown}{px}_i \overset{\frown}{\widetilde{mx}}_i + \overset{\frown}{pu}_i \overset{\frown}{\widetilde{mu}}_i . \qquad (6.12)$$

By rearrangement,

$$\overset{\frown}{pu}_i = \frac{\overset{\frown}{py}_j(\overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j) - \overset{\frown}{px}_i \overset{\frown}{\widetilde{mx}}_i}{\overset{\frown}{\widetilde{mu}}_i}, \ \overset{\frown}{\widetilde{mu}}_i \neq 0 ,$$

and by substitution of $\overset{\frown}{\widetilde{mu}}_i$ for $\overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j - \overset{\frown}{\widetilde{mx}}_i$ as per Equation 6.7,

$$\overset{\frown}{pu}_i = \frac{\overset{\frown}{py}_j(\overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j) - \overset{\frown}{px}_i \overset{\frown}{\widetilde{mx}}_i}{\overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j - \overset{\frown}{\widetilde{mx}}_i}, \ \overset{\frown}{\widetilde{my}}_j + \overset{\frown}{\widetilde{mv}}_j - \overset{\frown}{\widetilde{mx}}_i \neq 0 . \qquad (6.13)$$

Of course, an unknown domestic supply price per tonne for commodity j, $\overset{\frown}{pv}_j$, may be determined by substitution of the domestic use price per tonne for commodity i, $\overset{\frown}{pu}_i$, with its international export equivalent, $\overset{\frown}{px}_i$, using a similar set of equations. [166]

Step 4 Derivation of Domestic Supply-Use Physical Flows

The physical mass of commodities supplied and used domestically may be established using the prices per tonne generated in step 3. For example, the physical mass of each coefficient in the domestic supply matrix, $\widetilde{\mathbf{V}}$, may be derived in the following manner:

$$\widetilde{\mathbf{V}}_{ij} = \frac{\mathbf{V}_{ij}}{\overset{\frown}{pv}_j}, \ \overset{\frown}{pv}_j \neq 0 . \qquad (6.14)$$

[166] In some circumstances the import, export, domestic supply or domestic use price, or any combination of these, could be zero. Equations may be adjusted accordingly.

Similarly, the physical mass of each domestic use coefficient, as recorded in matrices **S**, **T** and **U**, may also be ascertained. The physical mass of each element, $\widetilde{\mathbf{U}}_{ij}$, in the domestic use matrix may, for example, be calculated as

$$\widetilde{\mathbf{U}}_{ij} = \frac{\mathbf{U}_{ij}}{\overline{pu_i}}, \ \overline{pu_i} \neq 0 . \qquad (6.15)$$

Step 5 Insertion of Superior National Data

Trade-based prices per tonne were not solely used to determine domestic physical flow. Some 46 commodity groups, consisting predominantly of the larger physical flows in the New Zealand economy, were determined from the insertion of superior *ad hoc* data taken from various sources including Statistics New Zealand, producer boards, industry and academic publications. These superior data insertions are summarised in Table 6.3. It is worth noting that rather than being based on prices per tonne of commodity, these sources tended simply to record total tonnage produced. Adjustments were required in some cases to take account of already determined import and export tonnages, any moisture content that had been removed from the commodities, and other lesser issues. Furthermore, data was used in some cases to verify physical flows calculated from the trade-based price per tonne estimates generated in steps 2 and 3.

Table 6.3 Superior Data Inserted into the New Zealand Physical Input-Output Model, 1997-98

Commodity Group	Price $/tonne[1]	Data Sources	Notes
8 Sheep	1,817	SNZ (1998d, p.42) Burtt (1999, pp.A-12 to A-15)	Weighted average $ per tonne for ewes, rams, wethers and lambs
9 Cattle	2,132	Meat and Wool Economic Service of New Zealand (1999, pp.19,27)	Weighted average $ per tonne for beef cattle, breeding cows, dairy cows and heifers
10 Wool	4,489	New Zealand Wool Group (n.d.)	
11 Grain and other crops	252	Food and Agriculture Organisation of the United Nations (n.d.) Burtt (1999, pp. A-55 to A-64)	Weighted average $ per tonne for barley, wheat, maize and oats
14 Raw milk	406	Fonterra Co-operative Group (n.d.) Burtt (1999, p.A-30)	Milk solids were multiplied by a conversion factor of 8.42 to convert into wholemilk (M.G. Patterson, pers. comm., November 26, 2002)
15 Pigs	2,700	Burtt (1999, p.A-52) SNZ (1999d, p.42)	Weighted average $ per tonne for weaners, stores, porkers, sows and choppers
16 Poultry	4,250	Poultry Industry Association of New Zealand Inc. (n.d.) Burtt (1999, p.C-28)	
17 Deer	5,764	Ministry of Agriculture and Forestry (1998)	Weighted average $ per tonne for weaners, velvet stags and breeding hinds
23 Standing timber	39	Ministry of Agriculture and Forestry (1999, 2000)	Change in standing timber stock. Conversion from m^3 to tonnes required an adjustment for the density of *Pinus radiata* based on the U.S. Department of Agriculture (1974) and Patterson (1980)
30 Coal	92	Dang (1999, p.31)	
31 Metal ores	13	Christie, Brathwaite and Thompson (1993, pp.20-23) Ministry of Economic Development (1998) New Zealand Mining (1998, p.11)	Weighted average $ per tonne for ironsand and smaller quantities of various other metal ores for 1996. Prices adjusted from 1996 to 1998 using SNZ's Mining PPI (Outputs)
32 Building stone	246	Christie, Douch, Winfield and Thompson (2000, pp.15-25) New Zealand Mining (1998, p.11)	Price adjusted from 1996 to 1998 using SNZ's Mining PPI (Outputs)
33 Gypsum and limestone	13	Christie, Thompson and Brathwaite (2001a, pp.6-25) New Zealand Mining (1998, p.11)	Weighted average $ per tonne for limestone and dolomite for agriculture, roading and industrial use
34 Sand, pebbles, gravel, clay	16	Christie, Thompson and Brathwaite (2000, pp.26-43) Christie, Thompson and Brathwaite (2001b, pp.6-26) New Zealand Mining (1998, p.11)	Weighted average $ per tonne for sand, gravel, clay and rock for various activities including bricks, ceramics, pottery, roading, reclamation and industrial use. Price adjusted from 1996 to 1998 using SNZ's Mining PPI (Outputs)
36 Salt	332	Hogan and Williamson (1999, p.287)	
40 Crude petroleum and natural gas	257	SNZ Infos Series NRGA.SCR7ZM and NRGA.SGP3AM	Natural gas converted from TJ to tonnes using a ratio of 19.9 metric tonnes C per TJ (M.G. Patterson, pers. comm., November 26, 2002)
43 Poultry products	3,112	SNZ (2000, p.18)	
44 Bacon, ham and smallgood products	5,784	SNZ Infos Series PRPH.SAACD, PRPH.SAACE, and PRPH.SAACF	
46 Processed milk and cream	1,359	SNZ (2000, p.18)	

Table 6.3 Superior Data Inserted into the New Zealand Physical Input-Output Model, 1997-98 (Continued)

Commodity Group	Price $/tonne[1]	Data Sources	Notes
50 Prepared vegetables	1,132	New Zealand Vegetable and Potato Growers' Federation Inc. (n.d.)	
51 Fruit juices	1,870	Statistics New Zealand (1998a)	Weighted average $ per tonne for various fruit juices including orange, apple, currant, grape and combinations
54 Grain products	1,234	Department of Statistics (1981)	Weighted average $ per tonne for various bakery products recorded in the 1978-79 CoM[2]. Prices adjusted from 1979 to 1998 using SNZ's CPI for Grain Products
55 Starches	1,077	Department of Statistics (1981)	Weighted average $ per tonne for various bakery products recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ's CPI for Sugars and Sweeteners
56 Animal feedings	588	Department of Statistics (1981)	Weighted average $ per tonne for various animal feeds recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ's Food, Beverage and Tobacco PPI (Outputs)
57 Bakery products	2,685	Department of Statistics (1981)	Weighted average $ per tonne for various bakery products recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ's CPI for Bakery Products
58 Sugar	761	Department of Statistics (1981)	Weighted average $ per tonne for refined sugar and molasses as recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ CPI for Sugars and Sweeteners
59 Confectionery	8,373	Department of Statistics (1981)	Weighted average $ per tonne for various confectionary products recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ CPI for Sugars and Sweeteners
60 Macaroni and noodles	2,596	Department of Statistics (1981)	Weighted average $ per tonne for noodles, macaroni, spaghetti and vermicelli as recorded in the 1978-79 CoM. Prices adjusted from 1979 to 1998 using SNZ CPI for Pasta and Pastry
63 Soft drinks, bottled water	2,111	Statistics New Zealand Infos Series SEPQ.SABBA, SEPQ.SABBC, SEPQ.SABBD, SEPQ.SABBE and SEPQ.SABBF	
67 Yarn and thread	17,160	Statistics New Zealand Infos Series SEPA.SYZ	
73 Knitted fabrics	12,084	Statistics New Zealand Infos Series SEPA.SATTD	
77 Wood	415	Statistics New Zealand Infos Series FLTA.SBEA3	Conversion from m^3 to tonnes required an adjustment for the density of sawn timber based on the U.S. Department of Agriculture (1974) and Patterson (1980)
78 Panels and boards	563	Statistics New Zealand Infos Series FLTA.SMAA, FLTA.SMBA and FLTA.SBDA	Conversion from m^3 to tonnes required an adjustment for the density of plywood and panels based on the U.S. Department of Agriculture (1974) and Patterson (1980)
83 Pulp, paper and paperboard	1,022	Statistics New Zealand Infos Series FLTA.SPFA and FLTA.SPGA	
97 Fertilisers	254	Statistics New Zealand Infos Series MAGQ.SAB	
101 Articles of concrete and stone	221	Statistics New Zealand Infos Series SEPA.SAFRZM	
140 Water	0.77	McDermott Fairgray Group Ltd (1998) McDermott Fairgray Group Ltd and Massey University (1999) Patterson and McDonald (2004)	Reticulated household water use calculated as weighted average m^3 per person per day for Waitakere, North Shore, Auckland and Manukau cities. Scaled from cities to the nation based on population estimates. Reticulated industrial use calculated m^3 per FTE for Northland, Auckland and Waikato region industries. Scaled from regions to the nation based on FTE estimates

Notes:

1. 1998 New Zealand Dollars.
2. Census of Manufacturing.

Step 6 Estimation of Service Sector Physical Flows

Of a possible 210 commodities, some 80 represent service commodities. Generally speaking, the provision and use of service commodities results in negligible physical flows – limited mainly to paper flow. Several notable exceptions do however exist including takeaways, computer software and photographic services. Such physical flows were estimated form *ad hoc* data obtained from various statistical, industry and academic sources. The physical flow of takeaways, for example, was determined by taking a weighted average price per tonne of commonly consumed fast foods.

Paper flow associated with the delivery or use of a service commodity is typically informational (e.g. written reports), administrative/accountancy based (e.g. invoices, receipts, purchase orders) or advertising/packaging related (e.g. envelopes, cardboard boxes). Thus, paper flow is a by-product of service provision or use. Crude estimates of service industry paper flow were generated by assuming that a relationship exists between the mass of the paper and paperboard products purchased by the service industry, on the one hand, and the final paper outputs delivered, on the other hand. Paper inputs were transformed to paper outputs by multiplying paper inputs by a wastage percentage obtained from *ad hoc* sources. Further research into other possible approaches or minimally surveying of service industry paper waste flows is, however, required to substantiate/improve the estimates generated.

Commodity 210 of the national financial supply-use framework represents direct purchases abroad by residents. It comprises primarily the purchases made by New Zealanders while travelling abroad. The physical mass of such purchases was crudely estimated by assuming industry purchase patterns overseas mirrored purchase patterns domestically. In this way, the physical mass of commodity 210 purchased by a particular industry was determined by spreading the financial value, on a pro-rata basis, over all other purchases made by the industry, and applying their price per tonne figures.

6.1.3 Derivation of an Auckland Region Physical Input-Output Model

Step 7 Derivation of Regional Physical Flows

Crude estimates of physical flows in the Auckland Region economy were generated by assuming that national prices per tonne, both for domestic consumed/produced and traded commodities, were spatially invariant. In other words, Auckland Region prices per tonne for a commodity were set to be equivalent to national prices per tonne. In mathematical terms:

$$\widehat{px}_i^r = \widehat{px}_i,\ \widehat{py}_j^r = \widehat{py}_j$$

and either $\widehat{pu}_i^r$ was assumed to be equal to $\widehat{pu}_i$, or $\widehat{pv}_j^r$ equal to $\widehat{pv}_j$. In the case of interregional trade, the price per tonne for interregional imports was assumed to be equal to $\widehat{pv}_j$, while the price per tonne for interregional exports was assumed to equate to $\widehat{pu}_i$. The remaining unknown $\widehat{pu}_i^r$ or $\widehat{pv}_j^r$ were calculated at the regional level in an analogous manner to the procedure outlined in step 3. In this way, the Auckland Region supply and use matrices developed in Chapter 5 were transformed into physical equivalents by dividing financial flows by price per tonne figures.

Step 8 Insertion of Superior Regional Data

Once again an opportunity was provided for the capture of any *ad hoc* superior data that existed at the regional level. Under ideal conditions superior regional data should be inserted when the regional supply or use price per tonne differs significantly from its national equivalent. Such situations may arise with differences in business management practices (e.g. a business may prefer to purchase commodity inputs from a subsidiary at a higher price than a local producer), business size or scale (e.g. the presence, or absence, of economies/diseconomies of scale), business location (e.g. proximity to consumer markets, production networks, transportation hubs, natural resources), and so on.

In the few instances where primary data actually existed for Auckland Region, this was inserted into the physical supply-use matrices. Estimates of reticulated water use by Auckland Region businesses and residents, as obtained from metered recordings, for example, replaced the less accurate national price per tonne figures. Time constraints however prohibited a comprehensive literature search, surveying or interviewing of Auckland Region businesses. Despite a paucity of region-specific data, the estimates generated enable tentative results to be obtained.

Step 9 Aggregation of Industries and Commodities for Analytical Purposes

The final step in constructing the New Zealand and Auckland Region commodity-by-industry physical input-output model was the aggregation of the commodities and industries. Aggregation was undertaken for reasons of ease of analytical manipulation and reporting. The physical commodity-by-industry matrices were aggregated from 210 commodities by 123 industries to 48 commodities by 48 industries, and are available as Excel files ('New Zealand Physical Commodity-by-Industry Model.xls' and 'Auckland Region Physical Commodity-by-Industry Model.xls') in the Chapter 6 directory of the accompanying CD-ROM. These matrices were further aggregated to 3 commodities by 3 industries and are presented in Appendix H.

6.1.4 Derivation of Raw Material and Residual Flows for the Auckland Region/National Economy

The methodology created above to estimate the physical mass flows within the New Zealand and Auckland Region economies assures commodity mass balance, i.e. the mass of each commodity supplied equal the mass of the commodities used (or stored). At an industry level, however, mass balances must also exist, i.e. the mass of commodities inputs into an industry must equal the mass of commodities outputs (included those placed in storage) produced by that industry. This requires consideration of commodities not normally valued in economic production, namely: (1) raw materials that flow from the environment to the economy[167] (e.g. nutrients, water, oxygen and carbon dioxide), and (2) residuals that flow from the economy to the environment[168] (e.g. wastes, pollutants, emissions).[169] These physical flows are represented in Table 4.2 by matrices $\tilde{\mathbf{C}}, \tilde{\mathbf{D}}, \tilde{\mathbf{E}}, \tilde{\mathbf{F}}, \tilde{\mathbf{G}}, \tilde{\mathbf{H}}, \tilde{\mathbf{K}}, \tilde{\mathbf{L}}, \tilde{\mathbf{O}}, \tilde{\mathbf{P}}$ and $\tilde{\mathbf{Q}}$.

There are currently no internationally recognised classifications systems or guidelines governing the recording of the physical flow of materials/residual associated with economic activity. The SEEA system is perhaps the most advanced, but is not comprehensive in its coverage or implementation. Other possibilities include systems utilised in economy-wide material flow accounting (e.g. Adriaanse *et al.* (1997) and Steurer and Shütz (2000)), national resource accounting (e.g. the French Patrimony Accounts, Norwegian Natural Resource Accounts), MIPS/Factor 10 type analyses (Schmidt-Bleek, 1994a, 1994b, 1994c, 1997), and German/Danish PIOT models. Given that the physical flow accounting framework presented in Chapter 4 is comprehensively similar to the German PIOT, the major categories of the latter are adopted to classify the physical flows of Auckland Region's environment-economy interface (Table 6.4).

[167] Residuals, particularly construction or demolition waste, may also flow from the environment to the economy.

[168] Raw materials, such as livestock, may also be considered to flow from the economy to the environment.

[169] Raw material and residual inputs flowing from the environment to the economy are sometimes recorded as 'free goods of nature'. This terminology is however considered inappropriate in this context as raw materials/residuals are included irrespective of whether they are provided free by nature or traded through markets. Coal, for example, requires two commodities to describes its physical flow: (1) in-ground coal (which has no price), and (2) mined coal (which has a price). Although subtle this distinction is important.

Table 6.4 Classification of Raw Materials and Residuals

	Major Category	Category	Sub-category	Item
Raw Materials	Soil excavation for structures			
	Water raised			Water takes
	Oxygen			Combustion
				Farm animal breathing
	Carbon dioxide			Land plant respiration
	Other air components (nitrogen etc.)			
Residuals	Wastes for economic re-use	Solid waste	Recycled solid waste	Aluminium
				Glass
				Paper
				Plastic
				Steel
	Wastes for treatment, storage	Solid waste	Landfill solid waste	Construction and demolition waste
				Metal
				Glass
				Plastic
				Paper
				Potentially hazardous
				Organic matter - kitchen and garden waste
				Other
			Cleanfill solid waste	Construction and demolition waste
	Waste water			Water discharges
	Other materials discharged into nature	Water pollution	Point source water pollution	Biochemical Oxygen Demand
				Dissolved Reactive Phosphorus
				Total phosphorus
				NH_4
				Total Kjedahl nitrogen
				NO_3
			Non-point source water pollution	N
				P
		Air emissions	Energy use emissions	CO_2
				NO_2
				CH_4
			Non-energy industrial air emissions	CO_2
				PM10
				CO
				NOx
				SOx
				VOC
			Vegetation/land cover emissions	CH_4
				CO
				H_2S
				N_2O
				NMHC
				NO
				NO_2
				NOx
				VOC
			Farm animal emissions	CH_4
				NH_3

The Tables presented below provide brief summaries of the methodological process undertaken in calculating the physical flows of raw materials (Table 6.5) and residuals (Table 6.6) across the environment-economy interface. In total 18 raw material inputs, in matrices $\tilde{\mathbf{F}}, \tilde{\mathbf{G}}, \tilde{\mathbf{H}}$ and $\tilde{\mathbf{K}}$, and residual inputs, in matrices $\tilde{\mathbf{C}}, \tilde{\mathbf{D}}$ and $\tilde{\mathbf{E}}$ were estimated. By contrast, a total of 43 raw material outputs, in matrix $\tilde{\mathbf{Q}}$, and residual outputs in matrices $\tilde{\mathbf{L}}, \tilde{\mathbf{O}}$ and $\tilde{\mathbf{P}}$ were estimated. Only brief methodological summaries are provided as papers/technical reports with comprehensive methodologies have been published elsewhere by the author. This includes technical reports from the *Eco*Link Project[170] (i.e. McDonald (1997), McDonald *et al.* (1999), and McDonald and Patterson (1999). There reports were independently peer-reviewed by Barton (2001), Cole (2001) and Zanders (2002). Other estimates have been derived through the Ecological Footprint Plus (WROX0305) and Sustainable Pathways (MAUX0306) FoRST programmes. A detailed analysis of Auckland Region's raw material and residual physical flows is provided in Appendix I.

Table 6.5 and Table 6.6 describe the calculation of not only estimates relevant to this thesis, but also estimates generated for the Ecological Footprint Plus and Sustainable Pathways FoRST programmes. Refereed publications applying this extended dataset include: McDonald and Patterson (2003b, 2003c, 2004), Patterson and McDonald (2004), Jollands, Golubiewski and McDonald (2005, in press a), and McDonald *et al.* (in press).

[170] The *Eco*Link project was undertaken between June 1996 and August 2000. It was jointly funded by the Ministry for the Environment's Sustainable Management Fund (Contract Nos. 5052, 5081 and 5109) and nine local authorities (including Auckland Regional Council and its constituent City councils) to the value of $355,000. The focus of the project was on developing an integrated economic-environmental accounting software toolkit to aid local government policy and decision makers. For each territorial local authority *Eco*Link provided estimates, at the detailed industry level, of: (1) economic activity; (2) resource use (water, energy and land); (3) residual generation (point source water pollution, energy related air emissions); and (4) various eco-efficiency indicators and economic aggregates.

Table 6.5 Data Sources for the Raw Material Inputs into the Auckland Region and New Zealand Economies, 1995-98

Major Category	Item(s)	Data Sources	Industry Coverage	Spatial Coverage	Temporal Coverage	Methodology
Water raised	Water takes	McDonald (1997) McDonald *et al.* (1999) McDonald & Patterson (1999)	48 industries and households	New Zealand, Auckland (54 catchments, 7 TLAs), Northland (30 catchments, 3 TLAs), Waikato (25 catchments, 12 TLAs) & Canterbury Regions	YE 31 Mar 1995, 1998	Refer to McDonald *et al.* (1999) for full details. Northland and Waikato are based on resource consents, while Auckland estimates are based on metered readings. New Zealand estimates were calculated for (1) each industry: m^3/FTE (as derived from Auckland, Northland and Waikato Regions) x FTEs, and (2) household consumption: m^3/capita x usually resident population.[1]
Oxygen	Combustion	EECA (1996, 2004) Patterson (2005)	48 industries and households	New Zealand, Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	The oxygen required for combustion was calculated using combustion equations taken directly from the Biogeochemical Cycling Model (refer to Patterson (2005)) for the following delivered energy types: aviation fuel, coal, diesel, electricity, fuel oil, geothermal, LPG, natural gas, petrol and wood.
Oxygen	Farm animal breathing	Statistics New Zealand (1999a)	Livestock and cropping [2], Dairy cattle farming [3] and Other farming [4]	New Zealand All Regional Councils	YE 31 Mar 1998	This required two steps (1) O_2 emission factor per head of livestock (t/head/yr) x number of livestock (head). Emission factors and livestock numbers were available for sheep, dairy cattle, beef cattle, pigs, deer, goats and chickens; and (2) for each industry summation of emissions across relevant livestock types.
Carbon dioxide	Land plant respiration	Patterson (2005)	Hort & fruit growing [1], Livestock and cropping [2], Dairy cattle farming [3], Other farming [4], Forestry & logging [6] and Households [49]	New Zealand All Regional Councils	YE 31 Mar 1998	The CO_2 required for land plant respiration was calculated using equations taken directly from the Biogeochemical Cycling Model (refer to Patterson (2005)).

Notes:

1. Water takes by industry (excluding hydro-electricity, but including irrigation and livestock consumption) was estimated to be 1,490 million m^3. This Figure compares favourably with independent estimates generated by the Ministry for the Environment (1997b) - 1,920 million m^3 (includes livestock consumption of 350 million m^3).

Table 6.6 Data Sources for the Residual Outputs from the Auckland Region and New Zealand Economies, 1995-98

Major Category	Category	Item(s)	Data Sources	Industry Coverage	Spatial Coverage	Temporal Coverage	Methodology
Wastes for economic re-use	Recycled solid waste	Aluminium, glass, paper, plastic, steel	Ministry for the Environment (n.d.b) Packaging Council of New Zealand Inc. (n.d.)	48 industries and households	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	Based on estimates derived from the New Zealand Packaging Council. Split across industries based on outputs from aluminium industry [21] (aluminium), nn-mtllc mnrl prdct manuf [20] (glass), paper & paper prdct manuf [16] (paper), rub, plstc & chem prdct manuf [19] (plastic), and steel industry [21] (steel).
Wastes for treatment, storage	Landfill solid waste	Construction and demolition waste, metal, glass, plastic, paper, potentially hazardous, organic matter - kitchen & garden waste, other	Ministry for the Environment (1997a) Street (1998) Ministry for the Environment (n.d.a)	48 industries and households	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	Based on estimates derived by Street (1998). This required: (1) updating of Street's 1996 base year to 1998 (performed at an aggregated 5 industries plus households), & (2) splitting of Street's 5 industries into 48 industries. This was performed using: (1) output figures for construction [29] (construction and demolition waste), industries involved in metal product manuf [21, 22, 23 & 24] (metal), nn-mtllc mnrl prdct manuf [20] (glass), rub, plstc & chem prdct manuf [19] (plastic), paper & paper prdct manuf [16] (paper), all manuf industries (potentially hazardous), industries producing kitchen & garden waste (organic matter - kitchen & garden waste), & (2) gross output figures for all industries (other).
Wastes for treatment, storage	Cleanfill solid waste	Construction and demolition waste	Auckland Regional Council (1996) Ministry for the Environment (1997b)	Construction [29]	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	Taken directly from Ministry for the Environment (1997b). The literature estimate is for the year ending 31 Mar 1996. It was updated to 31 Mar 1998 using FTE growth in the Construction [29] industry.
Waste water		Water discharges	McDonald (1997) McDonald *et al.* (1999) McDonald & Patterson (1999)	48 industries and households	New Zealand Auckland (54 catchments, 7 TLAs), Northland (30 catchments, 3 TLAs), Waikato (25 catchments, 12 TLAs) & Canterbury Regions	YE 31 Mar 1995, 1998	Refer to McDonald *et al*. (1999) for full details. Auckland, Northland, Waikato are based on resource consents. New Zealand estimates were calculated for (1) each industry: m^3/FTE (as derived from Auckland, Northland and Waikato Regions) x FTEs, and (2) household consumption: m^3/capita x usually resident population.
Other materials discharged into nature	Point-source water pollution	Biochemical Oxygen Demand, Dissolved Reactive Phosphorus, Total Phosphorus, NH_4, Total Kjeldahl Nitrogen, NO_3	McDonald *et al*. (1999) McDonald & Patterson (1999)	48 industries and households	New Zealand Auckland (54 catchments, 7 TLAs), Northland (30 catchments, 3 TLAs), Waikato (25 catchments, 12 TLAs) & Canterbury Regions	YE 31 Mar 1995, 1998	Refer to McDonald *et al*. (1999) for full details. Applies standard values for various economic activities to annual volumetric flows to estimate BOD, DRP, total P, NH_4, TKN, & NO_3 production (e.g. t of BOD, DRP, total P, NH_4, TKN, & NO_3 per m^3 of cowshed wash down). Annual volumetric flow estimates were adjusted for seasonality, intermittedness of industrial operation and, as appropriate, other miscellaneous factors.

Table 6.6 Data Sources for the Residual Outputs from the Auckland Region and New Zealand Economies, 1995-98 (Continued)

Major Category	Category	Sub-category	Item(s)	Data Sources	Industry Coverage	Spatial Coverage	Temporal Coverage	Methodology
Other materials discharged into nature	Non-point source water pollution		N	Cooper & Thomsen (1988) Environment Waikato (1998) Judge & Ledgard (2002)	Hort & fruit growing [1], Livestock and cropping [2], Dairy cattle farming [3], Other farming [4] & Forestry & logging [6]	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	N emission factor (t/ha/yr) x land use (ha). The emission factors were for each farm type from Patterson (2002), Judge & Ledgard (2002), Cooper & Thomsen (1988), and Environment Waikato (1998).
Other materials discharged into nature	Non-point source water pollution		P	Cooper & Thomsen (1988) Environment Waikato (1998) Judge & Ledgard (2002)	Hort & fruit growing [1], Livestock and cropping [2], Dairy cattle farming [3], Other farming [4] & Forestry & logging [6]	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	P emission factor (t/ha/yr) x land use (ha). The emission factors were for each farm type from Judge & Ledgard (2002), Cooper & Thomsen (1988), and Environment Waikato (1998).
Other materials discharged into nature	Air Emissions	Energy use emissions	CO_2, NO_2, CH_4	EECA (1996)	48 industries and households	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1995, 1998, 2001, 2002, 2004	Refer to McDonald *et al*. (2004) for full details. Uses the same methodology used to generate the EECA (2002) database, but produces estimates for 48 rather than 33 industries.
Other materials discharged into nature	Air Emissions	Non-energy industrial	CO_2, PM10, CO, NOx, SOx, VOC	Cole (2001)	48 industries and households	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	CO_2, PM10, CO, NOx, SOx & VOC emission factors (t/FTE/yr) x FTEs. The emission factors were obtained from Cole's (1999) study of the Waikato Region.
Other materials discharged into nature	Air Emissions	Vegetation/ land cover emissions	CH_4, CO, H_2S, N_2O, NMHC, NO, NO_2, NOx, VOC	Environment Protection Authority (1997) Kuschel & Kingsland (1998) Kuschel & Petersen (1999)	Hort & fruit growing [1], Livestock and cropping [2], Dairy cattle farming [3], Other farming [4] & Forestry & logging [6]	New Zealand Auckland, Northland, Waikato & Canterbury Regions	YE 31 Mar 1998	Emissions factors from Kuschel & Kingsland (1998) were applied to LCDB vegetative types to generate CH_4, CO, H_2S, N_2O, NMHC, NO, NO_2, NOx & VOC emissions. Estimation of the emissions from each industry required: (1) multiplication of each vegetative type (ha) by its appropriate emissions factor (t/ha/yr) for each of the CH_4, CO, H_2S, N_2O, NMHC, NO, NO_2, NOx & VOC emissions, and (2) summation of each of the emissions (for CH_4, CO, H_2S, N_2O, NMHC, NO, NO_2, NOx & VOC) across all vegetative types. A GIS 'cookie cut' of the LCDB by Agribase was used to generate ha estimates of vegetative cover by industry.
Other materials discharged into nature	Air Emissions	Farm animal emissions	CH_4, NH_4	Statistics New Zealand (1999a)	Livestock and cropping [2], Dairy cattle farming [3] & Other farming [4]	New Zealand All Regional Councils	YE 31 Mar 1998	This required two steps: (1) fermentation and manure emission factors for CH_4 & NH_3 per head of livestock (t/head/yr) x number of livestock (head). Emission factors and livestock numbers were available for sheep, dairy cattle, beef cattle, pigs, deer, goats and chickens; and (2) for each industry, summation of each of the emissions (CH_4 & NH_3) across relevant livestock types.

6.1.5 Limitations of the Physical Input-Output Models

There are several limitations to the physical input-output models (New Zealand and Auckland Region) that were derived by the methodology described in Sections 6.1.1 to 6.1.3, in addition to those already mentioned. These include limitations related to: (1) using trade-based prices per tonne, (2) the system boundary, (3) inaccuracies in the economic input-output models, which were the starting point for their physical counterparts, and (4) incomplete and less-than-ideal physical data for insertion as superior data.

Limitations of using trade-based prices per tonne

- *Import and export exclusions.* A number of commodity exclusions exist in the NZHSC system. Export exclusions include goods consigned to the New Zealand armed forces or diplomatic representatives overseas; goods consigned for modification or repair[171]; second hand clothing for foreign aid projects; and aircraft parts for New Zealand aircraft based overseas or unserviceable parts removed from foreign aircraft and being returned overseas. Import exclusions include goods imported for use by foreign armed forces; fish landed by New Zealand vessels; returnable samples and in-transit goods; goods for officials of other countries; and passenger baggage imported permanently. Exclusions that apply to both exporting and importing include currency transactions in gold, silver or New Zealand coins; consignments valued under $1,000; and goods on loan.
- *Coding errors.* Overseas trade data is provided by exporters/importers and their agents to the New Zealand Customs Service. Considerable reliance is placed on the exporters/importers and their agents in submitting codes and information. Although Statistics New Zealand validates data and corrects errors where possible, there is no warranty that the NZHSC data they produce is completely free from error.
- *Quality improvement and price.* Consideration must be given to any adjustments which may have been made to the trade-based price per tonne figures for quality changes. If an apparent price increase of 5 percent accompanies an increase in the quality of a commodity, then national accounting practitioners will say that the quantity of the commodity has increased by 5 percent, even though the actual physical mass may remain the same.

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[171] It is anticipated that physical mass flow associated with repaired goods will balance out, assuming that such goods are exported and imported within the same given year.

System boundary limitations

- *Residence rather than territory.* SNZ typically defines the national economy as the activities and transactions of producers and consumers that are resident, i.e. have their centre of economic interest with the nation. Some activities may however occur outside the nation or be undertaken by non-residents, e.g. tourism. Consistency of financial and physical matrices means application of a 'residence' rather than 'territory' principle, i.e. materials purchased by resident units abroad would have to be considered material inputs into the economy, while materials extracted or purchased by non-residents would have to be identified and excluded.
- *Lack of international protocols.* To date comprehensive physical flow models (in the form of PIOTs) have only been developed for the Netherlands, Germany and Denmark and, as such, conventions and protocols are still in their infancy. Although not strictly focused on comprehensive physical flow accounting, draft methodological guides for economy-wide Materials Flow Analysis (MFA) have been developed by Steurer and Schütz (2000). Other milestone publications have included *Resource Flows: the material basis of industrial economies* (Adriaanse *et al.*, 1997) and *The Weight of Nations – material outflows from industrial economies* (Matthews *et al.*, 2000). Although these initiatives are useful in guiding development, methods for dealing with peculiarities unique to New Zealand and its regions are required.

Inaccuracies in the economic input-output model

- *Inaccuracies of economic input-output models.* The economic input-output models generated in Chapter 5 (for New Zealand and Auckland Region) have inbuilt inaccuracies and limitations. Since both of these models are used as the starting point[172] to calculate mass flows in the counterpart physical models, any errors inherent in the economic models will be translated into the physical models. This particularly applies to the Auckland Region model where there are a number of errors implicit in the regionalisation process – refer to Chapter 5 for further discussion.

Incomplete and less-than-ideal physical data for insertion as superior data.

- *Validation of superior data.* Although significant effort was directed at inserting superior physical data, particularly at the national level, further effort is required to

[172] That is, financial flow data ($) in the economic input-output models are divided by the pricing data ($/tonne) in order to calculate physical flow data (tones) in the physical input-output models.

thoroughly validate this information. Among other things, this would consider: (1) exclusions (i.e. are certain sub-commodities excluded or not covered in aggregate figures), (2) gross versus net weights (i.e. is packaging included), (3) 'dry' versus 'wet' weights (i.e. has water been removed), (4) conversions (e.g. from volume to mass), and so on.

- *Industry rather than economy-wide superior data.* Most of the superior data inserted represents economy-wide physical use or supply; with the distribution across industries assuming price invariance. With further effort it may be possible to assign superior data to specific industries; greatly improving the accuracy of the model and therefore the estimation of the physical interdependencies between industries.
- *Superior regional data.* To improve the Auckland Region physical input-output model, further effort is required to search out or generate superior regional data. This would require *inter alia*: (1) collection of primary data through survey, (2) a less time constrained literature search, and (3) interviews with industry experts.

6.2 Analysis of Physical Flows in Auckland Region's Economy

6.2.1 Overview of Physical Flows

A conceptualisation of Auckland Region's overall metabolism is presented in Figure 6.2. In Figure 6.2 the 48 industries of the physical input-output model are represented in aggregated form using three industries, namely: agriculture, manufacturing and services. Domestic consumption of physical commodities is denoted by the label 'domestic consumption and capital formation'. Physical inflows into the economy include: (1) raw material inputs (111,793 kt) – 91,681 kt of this is water takes (water extracted directly from the environment), while 10,721 kt is oxygen for combustion and 9,910 is CO_2 for land plant respiration; (2) residual inputs (1,779 kt) -–capital formation in the form of man-made assets (controlled landfills) comprising wastes for treatment and storage; and (3) imports from other regions and nations (15,082 kt). Physical outflows from the economy include (1) exports to other regions and nations (9,621 kt), and (2) residual outputs (109,789 kt) – waste water discharged into the environment accounts for 97,075 kt of this, CO_2 emissions account for 9,224 kt, and landfill solid waste comprises 1,779 kt. Within the economy the inter-industry processing produces 49,957 kt of physical commodities for domestic consumption and capital formation, of which water consumption makes up 45,903 kt or 92.0 percent. Some industry (45 kt) and domestic consumption (41 kt) wastes are also recycled within the economy.

In Figure 6.2 the inter-industry physical flows are recorded from a use rather than supply perspective. This includes the use of some 101,094 kt of reticulated water – which constitutes more than 77 percent of all physical use within the Auckland Region economy. Consider, for example, three of the largest physical flows occurring within the economy: (1) manufactured commodities used by manufacturing (53,647 kt); (2) manufactured commodities used by service (11,622 kt) industries; and (3) commodities use by domestic consumption and capital formation (49,957 kt). Of these three flows, water supply constitutes 85.7 percent, 78.4 percent and 92.0 percent respectively. Similarly, waste water physical flow, 97,104 kt, is the key ingredient in residual outputs, 109,876 kt, flowing from the economy into the environment.

One important policy implication that may be drawn out of Figure 6.2 is that Auckland Region's economy is characterised by a 'throughput' rather than 'circular' metabolism i.e. re-use of residuals as raw materials is minimal. If this profile were to persist as Auckland Region grows (i.e. ignoring eco-efficient technological change, substitution effects or any trend toward circular metabolism) then increasing quantities of resources, and residuals, will be required. Not only would this mean increased pressure on the Region's environment to assimilate wastes and provide resources[173], but also on regional infrastructure such as water supply, sewerage systems, wastewater systems, transport networks, landfills, cleanfills and so on.

[173] Given that Auckland Region appropriates much of its goods and services from other regions and nations (refer to the balance of trade analyses in Chapters 5 and 6, along with the interregional trade optimisation of Chapter 8 and Appendix C) this is not likely to be a localised effect.

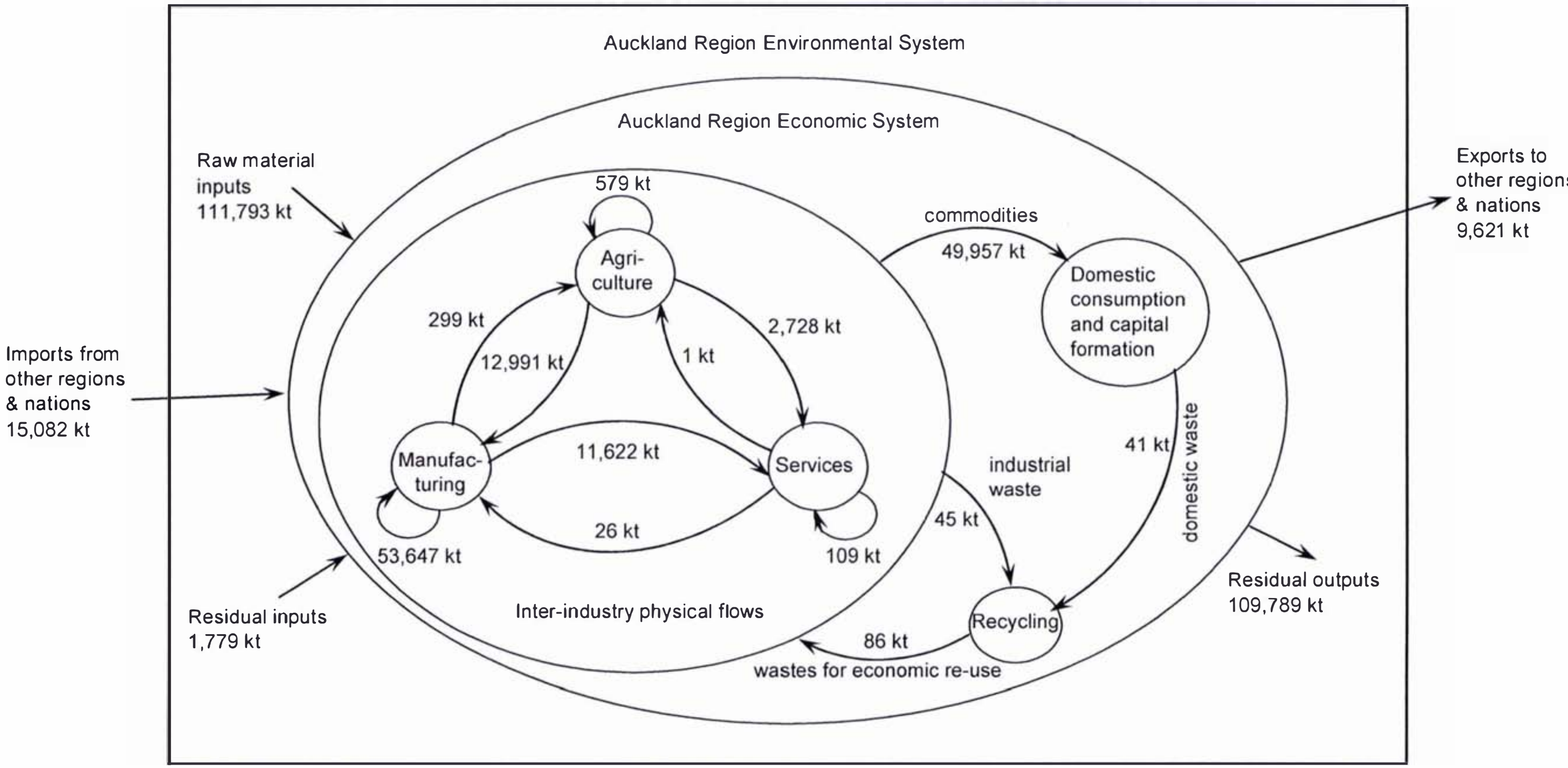

Figure 6.2 **Auckland Region's Major Environment-Economy Physical Flows, 1997-98**

6.2.2 Sectoral Physical Flows: Network Diagram

6.2.2.1 Explanation of the Network Diagram

The physical supply and use of commodities by certain key industries in the Auckland Region, and the interlinkages between them, is depicted in Figure 6.3. The industries featured were chosen by ranking the 48 industries in the physical input-output model according to both their total physical supply and total physical use, and then selecting the top 17 in terms of supply and the top 17 in terms of use. The water supply [28] industry ranked highest in both physical supply and use terms and, due to its disproportionately large flow volumes, was excluded from the analysis, leaving 16 industries for each of supply and use. As nine of the industries were both top users and suppliers of physical commodities, resulting in some overlap, the final selection included 23 industries. In addition, households are added to represent final demand.

Sector Commodity Flows: For each of the top 16 supply industries, its largest commodity supply flow to its corresponding major user is depicted in Figure 6.3. The gas supply [27] industry, for example, was the eighth largest commodity supplier in mass terms, supplying a total of 1,298 kt of commodities, all of which comprises oil and gas products. The largest user of oil and gas products is the wholesale trade [30] industry, hence the major commodity flow is depicted as a red arrow exiting gas supply and entering wholesale trade. Similarly, for each of the top 16 use industries, its largest commodity use flow from its corresponding major supplier is also depicted. The construction [29] industry, for example, is the third largest user of commodities in mass terms, using a total of 4,261 kt of various commodities. Its largest single commodity use is 1,770 kt of mining and quarrying products, supplied by the mining and quarrying [8] industry. This commodity flow is depicted as a major red arrow from mining and quarrying to construction.

It is important to note that not all of an industry's commodity supply is destined to its major using industry, but is also supplied to other industries. Thus, not all of the gas supply [27] industry's 1,298 kt of oil and gas products is supplied only to wholesale trade, but is resupplied to gas supply [27] and also supplied to other industries such as petroleum and industrial chemical manufacturing [18]. These flows are depicted as red arrows branching off the main supply flow. Some of these arrows enter the industries depicted in Figure 6.3, while the short red arrow exiting the main flow at an angle represents supply to industries that are not depicted in the Figure, such as oil and gas products supplied to the electricity generation and supply [26] industry. In this way, the total supply of a commodity from one industry does not equal the total use of that commodity by another industry. Similarly, the total physical flow of a commodity used by an industry does not all originate from just one supply industry, but also from other supply industries. The construction [29] industry, for example, receives only some of its mining and quarrying requirements from the mining and quarrying [8] industry, with the remainder received from other industries. This is represented in the diagram by the short red line entering the main flow at an angle.

Once the major inter-industry linkages had been established, two further flows, a use inflow and supply outflow, were added to each industry to account for other economic commodities used and supplied respectively by that particular industry. These flows are represented by the short red arrows entering (use) and exiting (supply) the industry, but not connected to any other industry or commodity flow. The construction [29] industry, for example, in addition to the major commodity flows depicted, also used 267 kt of other commodities such as petroleum products and chemical, rubber and plastic products, and supplied 134 kt of other commodities such as mining and quarrying products and non metallic mineral products.

Environmental and Water Flows: To account for the environmental flows, namely raw material inputs and residual outputs, four further flows were added to each industry. The green inflows and outflows represent raw material inputs (less water takes) from, and residual outputs (less water discharges) to the environment, while the blue inflows and outflows similarly represent water takes from, and water discharges to, the environment.

Import and Export Flows. Note that Figure 6.3 does not record the physical flow of imports into the Auckland Region economy. This is not possible as physical imports are recorded by commodity rather than industry in Table 4.2, thus it is not possible to attribute imports to a particular industry. By contrast, exports may be included in Figure 6.3 in an analogous way to household consumption. Exports are not however included for reasons of balance. It is envisaged that future versions of the Auckland Region physical input-output model will be extended to assign commodity imports to industries. This would allow a more complete representation of Figure 6.3 to be developed.

6.2.2.2 Interpretation of the Network Diagram for Significant Industries

Wholesale trade [30]. In physical terms, this industry was the second largest commodity user and the third largest commodity supplier in the Auckland Region, reflecting its role as an intermediary or distributor. This industry's major use flow (i.e. inflow) was 1,794 kt of oil and gas products such as crude petroleum and natural gas. Most of this was supplied by the gas supply [27] industry with a small amount supplied by other industries such as oil and gas exploration and extraction [9] and imports. Wholesale trade also used 3,875 kt of other commodities from other industries, most of which comprises water (2,777 kt) from the water supply [28] industry, along with other commodities such as 302 kt of forestry and logging products, and 182 kt of petroleum products. The main supply flow was 2,884 kt of petroleum products, most of which was supplied to air transport, services to transport and storage [35], households, and retail trade [31]. The rest was supplied to other industries such as construction [29], represented by the small arrow exiting the main flow. Wholesale trade also supplied 1,010 kt of other commodities, such as basic metal products (221 kt), non metallic mineral products (206 kt), and chemical, rubber and plastic products (184 kt) to other industries. In addition, wholesale trade used 462 kt of raw material inputs, namely oxygen for combustion, and 18 kt of water extracted from the environment. The industry also produced 471 kt of residual outputs, mainly CO_2 emissions with some landfill solid waste, and discharged 2,658 kt of waste water into the environment.

Basic metal manufacturing [21]. This industry was the fourth largest user, and also the seventh largest supplier, of commodities in physical terms. Its main use flow was 3,532 kt of mining and quarrying products such as coal, building stone, gypsum and limestone, and sand, pebbles, gravel and clay. Most of this is supplied by the mining and quarrying [8] industry, with the rest supplied from other industries such as basic metal manufacturing itself, represented by the looped flow exiting basic metal manufacturing and re-entering the main flow from mining and quarrying to basic metal manufacturing, as well as non-metallic mineral manufacturing [20], construction [29] and other industries, represented by the short red line entering the main flow at an angle. Basic metal manufacturing also used 345 kt of other commodities such as basic metal products and petroleum products from other industries. There were two major supply flows from this industry. The first was 710 kt of mining and quarrying products, some of which was supplied to itself, with the rest going to other industries as represented by the short red arrow exiting the loop. The second was 708 kt of basic metals, some of which was supplied mainly to structural, sheet and fabricated metal product manufacturing [22] and machinery and equipment manufacturing [24], with the remainder going to industries such as retail trade [31] and wholesale trade [30]. Basic metal manufacturing also supplied 29 kt of other commodities, predominantly structural, sheet and fabricated metal products (27 kt), to other industries. Furthermore, 1,244 kt raw material inputs, namely oxygen for combustion, were used, while 982 kt of water was extracted from the environment. Basic metal manufacturing also supplied 1,074 kt of residual outputs, mostly CO_2 emissions, and 1,400 kt of waste water.

Non-metallic mineral product manufacturing [20]. This industry was the fifth largest commodity user in physical terms, and also the fourth largest commodity supplier. From a use perspective, this industry's main use flow was 3,175 kt of mining and quarrying products, such as building stone, gypsum and limestone, and sand, pebbles, gravel and clay, most of which is supplied from the mining and quarrying [8] industry. A portion of this 3,175 kt, represented by the short red line entering the main flow at an angle, is also supplied from other industries such as basic metal manufacturing [21] and construction [29]. From the supply perspective, this industry's main supply commodity was 2,290 kt of non-metallic mineral products, most of which was supplied to the construction [29] industry. Some of this 2,290 kt is also supplied to other industries such as petroleum and industrial chemical manufacturing [18], represented by the small arrow exiting the main flow. In addition, non-metallic mineral product manufacturing also used 427 kt of other commodities, mainly non-metallic mineral products, and supplies through joint production 168 kt of other commodities, predominantly mining and quarrying products. This industry also used 349 kt of raw material inputs, mainly oxygen for combustion, plus 184 kt of water extracted from the environment, and produced 1,180 kt of residual outputs, predominantly CO_2 emissions.

Other notable flows. The large water requirements of five industries are evident in the diagram, represented by the blue arrows entering them: Horticulture and fruit growing [1] (7,067 kt), dairy cattle farming [3] (4,713 kt), dairy product manufacturing [11] (3,819 kt), mining and quarrying [8] (3,789 kt) and beverage, malt and tobacco manufacturing [13] (1,584 kt). These flows comprise non-reticulated water as extracted directly from the environment. Not surprisingly, the largest residual output flows, represented by the green arrows exiting the industries, are produced by manufacturing industries such as paper and paper product manufacturing [16], non metallic mineral product manufacturing [20] and basic metal manufacturing [21]. These industries produce high levels of CO_2 emissions from their manufacturing processes. The construction [29] industry also produces a large residual flow, but this comprises mainly cleanfill solid waste, with small amounts of CO_2 emissions. The relatively high amount (2,716 kt) of raw material inputs into dairy cattle farming is made up predominantly of carbon dioxide for land plant respiration, reflecting the high quality pastures required for dairy cattle. Households, as a final demand sector, has no commodity supply flow, but uses by far the largest physical flow of commodities (47,730 kt), most of which (45,903 kt) is reticulated water from the water supply [28] industry. It also produces the largest residual flow (2,305 kt), of which 1,863 kt is CO_2 emissions, mainly from private transport, and 440 kt comprises recycled and landfill solid waste.

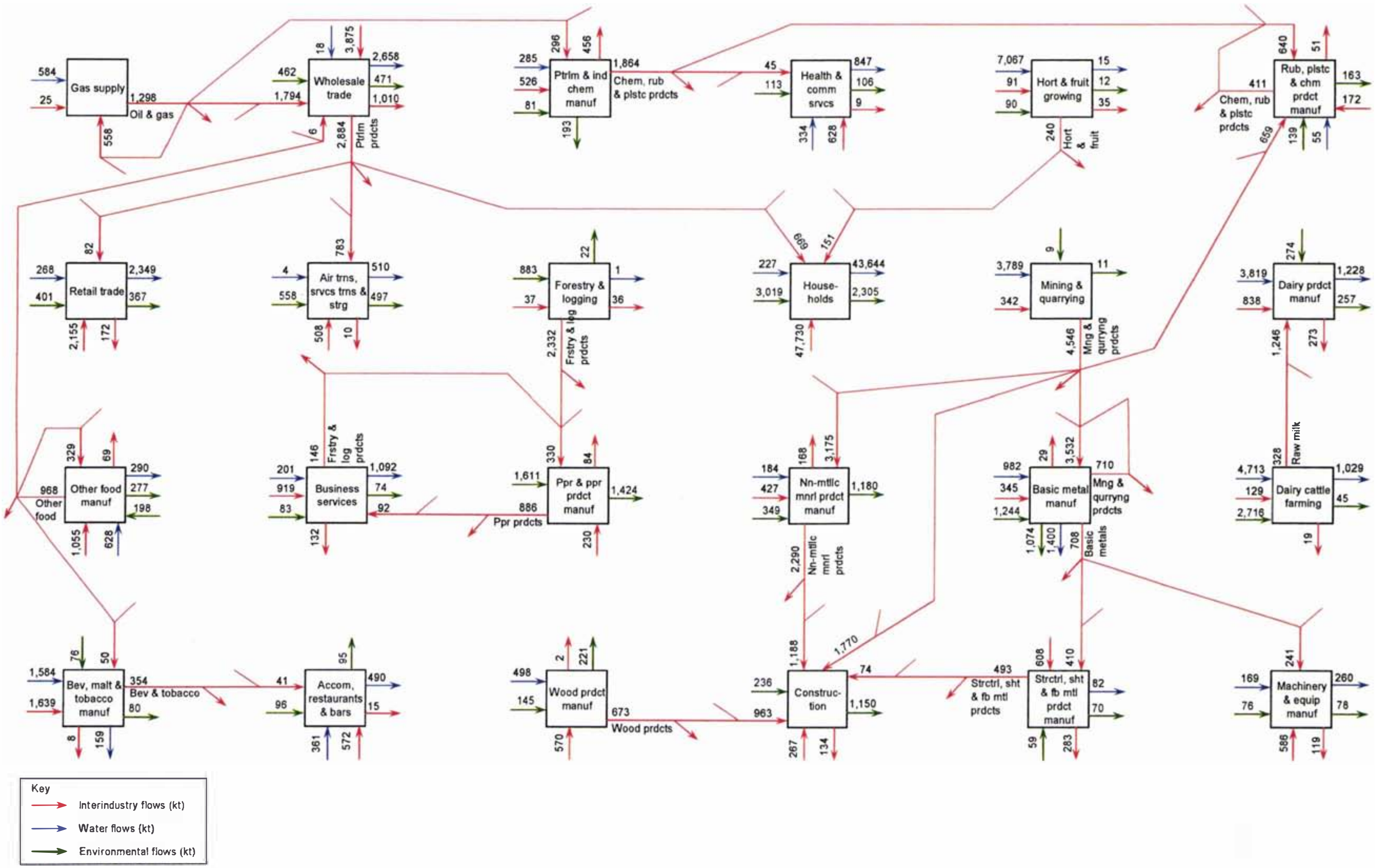

Figure 6.3 **Network Diagram of the Main Mass Flows in the Auckland Region Economy, 1997-98**

6.2.2.3 Key Interlinkages in the Network Diagram

Figure 6.3 shows some key interlinkages or clusters of industries from a physical perspective. The mining and quarrying [8] industry can be seen as a major physical supplier in the Auckland Region, supplying the major commodity used by industries such as rubber, plastic and chemical product manufacturing [19], non-metallic mineral product manufacturing [20], basic metal manufacturing [21], and construction [29]. The construction [29] industry, in turn, is a key user of physical commodities in Auckland Region, drawing supply from wood product manufacturing [15], non-metallic mineral product manufacturing [20], and structural, sheet and fabricated metal manufacturing [22]. Wholesale trade [30] has numerous flows entering and exiting, which reflects its role as an intermediary or distributor, linking it to industries such as gas supply [27], other food manufacturing [12], retail trade [31], air transport, services to transport and storage [35], and households.

6.2.3 Physical Balance of Trade

The physical input-output model enables a physical balance of trade by commodity type to be calculated for the Auckland Region (Table 6.7). This Table indicates that the Auckland Region is a significant net importer (5.5 Mt) of goods and services in physical terms[174], with 14.9 Mt of commodities appropriated from outside the region, while 9.4 Mt of commodities was exported. The bulk of Auckland Region's commodity imports originate from other regions in New Zealand (12.1 Mt), with 86.9 percent of this being primary commodities, emphasising Auckland Region's dependence on its surrounding hinterland for agricultural commodities for domestic consumption. Most of Auckland Region's exports were manufactured commodities, comprising 62.1 percent of total exports in mass terms. Not surprisingly, the service commodities once again reflect negligible physical flows, limited mainly to paper flow. One important policy implication that may be drawn out of Table 6.7 is that Auckland Region accumulated 5.5 Mt of mass during the study year. This will end up in either (1) landfills, (2) the environment, or (3) temporarily stored in capital goods (i.e. housing stock).

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[174] Auckland Region's physical balance of trade is in contrast to its financial balance of trade as discussed in Chapter 5. In financial terms, Auckland Region is a net exporter of goods and services, with interregional and international trade of similar magnitude.

Table 6.7 Physical Balance of Trade for the Auckland Region Disaggregated by Commodity Type, 1997-98 (kt)

Commodity Type	Imports	Exports	Balance of trade
Interregional trade			
Primary	10,498	2,356	-8,143
Manufacturing	1,613	3,306	1,694
Service	3	25	22
Interregional balance of trade	12,114	5,687	-6,427
International trade			
Primary	380	1,167	786
Manufacturing	2,400	2,754	354
Service	188	14	-174
International balance of trade	2,968	3,934	966
Balance of trade	15,082	9,621	-5,461

6.3 Ecological Multiplier Analysis: Combining Physical and Economic Flows

6.3.1 Rationale and Method

Ecological multipliers, which measure the total 'embodied resource' or 'embodied residual' required to produce $1 worth of a commodity in any given industry, are arguably an operational measurement of the eco-efficiency concept[175] – this includes all the resource/residual requirements appropriated over the commodity's cradle-to-grave lifecycle. Ecological multipliers may be calculated for any resource (e.g. water, minerals, biomass) or for that matter any residual (e.g. CO_2, BOD_5, SOx, NOx).

Ecological multipliers for the Auckland Region[176] are calculated for each resource input (e.g. water) and for each residual output (e.g. air emission, water pollutant and solid waste). Input-output analysis is one way of operationalising ecological multipliers (refer, for example, to Hite

[175] The World Business Council for Sustainable Development (WBCSD) introduced the concept of 'eco-efficiency' as one of its responses to the Rio Conference (DeSimone and Popoff, 2000). The concept of eco-efficiency is now beginning to have a significant impact not only in business, but also in the public policy (Hinterberger and Stiller, 1998). Eco-efficiency is defined by the WBCSD (2000, p.47) as: "the delivery of competitively-priced goods and services that satisfy human needs and brings quality of life, while progressively reducing environmental impacts and resource intensity throughout the lifecycle, to a level at least in line with the Earth's carrying capacity." Indicators based on the eco-efficiency concept attempt to link economic performance (producing competitively priced goods and services) to environmental costs (environmental degradation and natural resource depletion).

[176] The ecological multipliers calculated in this Section only account for indirect flows 'within the Auckland Region'. In most cases there are significant raw materials and residuals embodied in products from production outside the region (other regions, other countries). A full ecological multiplier analysis must take account of indirect flows from other regions/countries. Therefore, the ecological multipliers calculated in this Section are underestimates of the true situation. This limitation is overcome in Chapter 8, at least with respect to land inputs, by accounting for land embodied in production from other regions/countries in the ecological footprint analysis.

and Laurent, 1971, 1972; Wright, 1975; Carter *et al.*, 1981; Costanza and Neill, 1981). The key advantage of input-output analysis is that it relies on production chain data routinely collected by statistical agencies. The use of such data drastically reduces the need to collect primary data.

Essentially the ecological multipliers are calculated for the Auckland Region by combining data from the:

- *Economic input-output model* (Section 4.4.3.2, Chapter 5, Appendix F, Appendix G). Data on inter-industry transactions as may be calculated by applying the procedure outlined in Section 4.4.3.2 to the Auckland Region economic commodity-by-industry model generated in Chapter 5.
- *Physical input-output model* (Section 6.1.4, Appendix H, and Appendix I). Data on the raw material inputs and residual outputs, represented by the matrices $\tilde{H}, \tilde{K}$ and $\tilde{L}, \tilde{O}, \tilde{P}$ respectively.

Full details of the matrix algebra method used to calculate these multipliers and associated 'tree diagrams' are outlined in Chapter 7. The calculation is based on a method first developed by Costanza and Neill (1981) and enhanced by Patterson and McDonald (2004) to produce tree diagrams. It has the advantage over previous methods (e.g. Hite and Laurent, 1971) in that it can accommodate multiple industry outputs, rather than assuming that there is only one output per industry.

6.3.2 Ecological Multipliers for the Auckland Region

Table 6.8 presents a comparison of the ecological multipliers, as expressed in resource/residual units per $ million of economic output, for various resource inputs into the Auckland Region economy. In eco-efficiency terms an industry with a small ecological multiplier will require less resource input/residual output than an industry with a larger multiplier. This provides a mechanism for comparing the eco-efficiency of one industry against another.[177]

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[177] Comparison between industries is only relevant under certain circumstances – say, for example, in aiding a policy or decision maker to decide on which industry type to locate within a new development. It is less meaningful in the sense that an industry may supply a unique good or service and, thus, an eco-efficiency measure is only relevant when comparing between the different technologies or processes required to produce that good or service.

Table 6.8 Ecological Multipliers for Auckland Region's Economic Industries, 1997-98

Industry	Carbon Dioxide[1]	Nitrous Oxide[1]	Methane[2]	Water Takes[3]	BOD_5[4]	Phos-phorus[5]	Total Kjeldahl Nitrogen[4]	Solid Waste[6]
	t/$mil	kg/$mil	kg/$mil	kt/$mil	kg/$mil	kg/$mil	kg/$mil	t/$mil
1 Hort & fruit growing	127	12.0	546	28.0	1.61	0.82	1.10	7.6
2 Livestock & cropping	143	14.6	112,006	8.0	140.19	149.94	42.24	7.3
3 Dairy cattle farming	151	16.4	60,112	26.1	533.75	158.79	1.11	7.6
4 Other farming	266	26.8	9,596	7.9	1.71	1.37	1.23	9.4
5 Srvcs to ag, hnt & trppng	230	26.1	617	1.2	8.32	2.03	10.33	6.5
6 Forestry & logging	207	20.2	271	0.6	1.20	0.43	1.31	5.2
7 Fishing	519	70.6	94	3.4	0.70	0.16	0.92	2.8
8 Mining & Quarrying	148	20.3	68	31.5	0.60	0.15	0.70	24.5
9 Oil & gas explr & extrc	354	54.3	75	111.5	0.62	0.14	0.79	25.3
10 Meat & meat prdct manuf	198	29.6	3,752	7.2	10.04	5.87	9.07	78.0
11 Dairy prdct manuf	329	54.5	5,647	9.0	48.20	14.51	1.99	57.7
12 Other food manuf	234	25.8	445	2.9	2.09	0.77	2.09	25.4
13 Bev, malt & tobacco manuf	208	23.9	422	5.8	2.55	0.85	2.46	10.7
14 Textile & apparel manuf	144	17.0	1,567	3.1	3.12	2.24	1.96	9.8
15 Wood prdct manuf	376	29.0	136	2.7	1.56	0.36	1.88	122.7
16 Paper & paper prdct manuf	2,044	122.1	161	2.5	0.53	0.15	0.59	54.1
17 Print, pub & rec media	320	22.5	103	1.2	1.46	0.33	1.85	13.7
18 Ptrlm & ind chem manuf	260	27.8	162	2.4	1.23	0.32	1.45	82.5
19 Rub, plstc & chm prdct mnf	187	18.9	131	1.3	1.09	0.29	1.23	15.7
20 Nn-mtllc mnrl prdct manuf	643	120.1	130	3.5	0.76	0.19	0.91	18.1
21 Basic metal manuf	1,148	222.9	147	8.0	0.75	0.19	0.91	6.2
22 Strctrl, sht & fb mtl prdct	259	39.8	151	2.1	1.13	0.32	1.31	17.5
23 Transport equip manuf	129	16.2	96	1.1	0.95	0.24	1.16	10.2
24 Machinery & equip manuf	196	26.9	142	1.9	1.42	0.36	1.71	12.2
25 Furniture & other manuf	268	25.6	130	2.0	0.99	0.27	1.17	19.8
26 Elctrcty gnrtn & spply	24	2.6	20	82.2	1.21	0.23	1.66	5.8
27 Gas supply	29	3.3	30	6.3	0.49	0.11	0.62	2.0
28 Water supply	139	20.1	47	782.5	0.56	0.14	0.70	13.2
29 Construction	191	22.9	110	1.2	1.36	0.32	1.73	269.7
30 Wholesale trade	172	17.1	667	1.7	2.08	1.04	1.46	14.9
31 Retail trade	159	17.3	161	2.1	4.75	0.93	6.42	11.7
32 Accom, restaurants & bars	169	19.7	356	3.2	2.11	0.71	1.59	14.0
33 Road transport	1,367	131.5	525	0.7	1.38	0.29	1.83	14.9
34 Water & rail trans	642	89.6	200	0.8	0.50	0.19	0.50	3.8
35 Air trns, srvcs trns & strg	237	9.1	53	0.8	1.55	0.31	2.09	6.1
36 Communication srvcs	67	7.1	38	0.5	0.56	0.12	0.74	4.0
37 Finance	35	4.0	21	0.5	0.76	0.15	1.02	1.6
38 Insurance	33	3.2	20	0.5	0.67	0.13	0.91	2.1
39 Srvcs to fnnce & invstmnt	55	5.3	35	0.7	1.15	0.23	1.55	4.6
40 Real estate	51	5.6	70	9.6	0.68	0.19	0.76	17.4
41 Ownership OOD	35	3.7	27	9.1	0.82	0.16	1.10	15.8
42 Business srvcs	97	8.8	61	1.1	3.60	0.67	4.93	4.7
43 Central government	126	13.7	58	1.2	1.62	0.32	2.17	15.8
44 Local government	72	8.4	46	2.1	6.86	1.22	9.52	39.9
45 Education	63	9.1	35	1.1	1.12	0.22	1.50	6.9
46 Health & community srvcs	84	11.9	42	1.0	6.90	1.22	9.58	7.8
47 Cultural & rec srvcs	76	8.6	64	3.7	2.80	0.53	3.79	7.1
48 Personal & other comm srvcs	121	14.2	69	4.2	119.32	20.57	166.96	10.6

Notes:

1. Refers only to emissions from energy sources.
2. Refers to emissions from energy sources and farm animals.
3. Refers only to consented water takes covered under the Resource Management Act (1991).
4. Refers only to point source emissions.
5. Refers to point and non-point source emissions.
6. Refers to landfill and cleanfill solid waste.

The following key findings may be drawn out of Table 6.8:

- *Cumulative impacts.* All industries in the Auckland Region economy have a cumulative impact on the Region's environment. For many of these industries it is the less visible indirect contributions that are most important.
- *Energy related emission multipliers.* The multipliers for energy related air emissions (carbon dioxide, nitrous oxide), despite having significantly different delivered energy compositions, produce large ecological multipliers primarily in Auckland Region's manufacturing industries (paper and paper product [16], non-metallic mineral product [20], and basic metal [21] manufacturing). Of course, Auckland Region's role in import substitution through distribution of wholesale/retail commodities by way of road transport [33] is also evident.
- *Methane multipliers.* Methane emission multipliers are not surprisingly dominated by Auckland Region's livestock farming industries (livestock and cropping [2], dairy cattle farming [3], and other farming [4]). Sizeable multipliers are also derived for the economy's agricultural processing industries (meat and meat product [10] and dairy product [11] manufacturing), due to backward linkages within the economy.
- *Water pollutant multipliers.* The ecological multipliers for BOD_5, Phosphorus, and TKN show large multipliers in similar industries, namely livestock and cropping [2], dairy cattle farming [3] and other farming [4]. These results are not unexpected given the large direct contributions made by these industries – primarily the result of the use of fertilisers.
- *Solid waste multipliers.* The largest ecological multipliers for solid waste occur in the construction [29] industry, a result of the significant direct contribution made to cleanfill waste. Other significant contributions include wood and wood product [15], and petroleum and industrial chemical [19] manufacturing.

6.3.3 Cumulative Effects Indicator

In this Section a Cumulative Effects Indicator (CEI) is generated that may be applied at the industry level to assess the combined economic and environment effects of changes in economic activity. The CEI is formulated for a given industry by forming a relationship between the direct and indirect value added[178] (i.e. as calculated in Chapter 5) and direct and indirect ecological impact generated by that industry,

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[178] A Type I value added multiplier is utilised here as it is the multiplier than is most commonly used by economists in assessing the economic impact of changes in economic activity.

$$\frac{\overset{\frown}{\mathbf{ee}}}{\overset{\frown}{\mathbf{vae}}}, \tag{6.17}$$

where $\overset{\frown}{\mathbf{ee}}$ is the total direct and indirect environmental effect, and $\overset{\frown}{\mathbf{vae}}$ denotes the total direct and indirect value added effect. The key advantage of the CEI is that it establishes, for each resource input/residual output, a clear link between an industry's total embodied (i.e. direct and indirect) economic impact, and its total embodied (i.e. direct and indirect) environmental impact. CEI estimates for all industries in the Auckland Region economy are depicted in Table 6.9. Each cell in the Table represents the embodied raw material input/residual output required to produce a million $ of direct and indirect value added within a particular industry e.g. to produce a million dollars worth of direct and indirect value added, the finance [37] industry releases 76 tonnes of embodied CO_2 emissions. Overall, the lower the CEI, the greater the eco-efficiency of an industry in embodied terms.

Industries with high CEI values include dairy product manufacturing [11] – all resource inputs and residual outputs; dairy cattle farming [3] – methane, water takes, BOD_5, and phosphorous; livestock and cropping [2] – methane, BOD_5, phosphorus and TKN; paper and paper product manufacturing [16] – carbon dioxide and nitrous oxide; basic metal manufacturing [21] – carbon dioxide, nitrous oxide and solid waste; and personal and other community services – BOD_5, phosphorus and TKN. Lesser, but still significant CEI values include water supply [28] – water takes, road transport [33] – carbon dioxide and nitrous oxide, construction [29] and local government [44] – solid waste.

Table 6.9 Cumulative Effects Indicator for Auckland Region's Economic Industries, 1997-98

Industry	Carbon Dioxide	Nitrous Oxide	Methane	Water Takes	BOD_5	Phos-phorus	Total Kjeldahl Nitrogen	Solid Waste
	t/$mil	kg/$mil	kg/$mil	kt/$mil	kg/$mil	kg/$mil	kg/$mil	t/$mil
1 Hort & fruit growing	186	17.7	805	41.3	2.4	1.2	1.6	11.2
2 Livestock & cropping	258	26.5	202,767	14.6	253.7	271.5	76.5	13.1
3 Dairy cattle farming	178	19.3	70,981	30.8	630.3	187.5	1.3	9.0
4 Other farming	332	33.5	11,982	9.9	2.1	1.8	1.6	11.8
5 Srvcs to ag, hnt & trppng	325	37.0	874	1.6	11.7	2.8	14.5	9.2
6 Forestry & logging	152	14.9	200	0.5	0.9	0.3	1.0	3.8
7 Fishing	939	127.9	171	6.2	1.2	0.2	1.7	5.2
8 Mining & Quarrying	201	27.5	92	42.7	0.8	0.2	0.9	33.1
9 Oil & gas explr & extrc	412	63.3	88	129.9	0.6	0.0	0.6	29.7
10 Meat & meat prdct manuf	400	59.8	7,581	14.5	20.3	11.8	18.3	157.7
11 Dairy prdct manuf	1,450	240.4	24,899	39.7	212.5	64.0	8.8	254.6
12 Other food manuf	383	42.3	728	4.8	3.4	1.3	3.4	41.6
13 Bev, malt & tobacco manuf	247	28.4	501	6.9	3.0	1.0	2.9	12.7
14 Textile & apparel manuf	261	30.9	2,844	5.5	5.7	4.1	3.6	17.9
15 Wood prdct manuf	704	54.3	255	5.1	2.9	0.7	3.5	230.0
16 Paper & paper prdct manuf	2,712	162.0	213	3.4	0.7	0.2	0.8	71.8
17 Print, pub & rec media	428	30.1	138	1.5	1.9	0.4	2.5	18.3
18 Ptrlm & ind chem manuf	414	44.2	258	3.8	2.0	0.5	2.3	131.2
19 Rub, plstc & chm prdct mnf	300	30.3	210	2.2	1.8	0.5	2.0	25.3
20 Nn-mtllc mnrl prdct manuf	846	158.1	172	4.6	1.0	0.3	1.2	23.9
21 Basic metal manuf	2,205	428.2	283	15.5	1.4	0.4	1.8	11.9
22 Strctrl, sht & fb mtl prdct	359	55.2	209	3.0	1.6	0.4	1.8	24.4
23 Transport equip manuf	244	30.7	182	2.0	1.8	0.5	2.2	19.4
24 Machinery & equip manuf	282	38.6	203	2.8	2.0	0.5	2.5	17.5
25 Furniture & other manuf	454	43.4	220	3.4	1.7	0.5	2.0	33.5
26 Elctrcty gnrtn & spply	30	3.1	24	100.6	1.5	0.3	2.0	7.1
27 Gas supply	41	4.8	44	9.0	0.7	0.2	0.9	2.9
28 Water supply	160	23.0	54	895.8	0.7	0.2	0.8	15.2
29 Construction	273	32.7	158	1.7	1.9	0.5	2.5	385.5
30 Wholesale trade	219	21.8	850	2.1	2.6	1.3	1.9	19.0
31 Retail trade	205	22.3	208	2.7	6.1	1.2	8.3	15.1
32 Accom, restaurants & bars	240	28.0	507	4.5	3.0	1.0	2.3	20.0
33 Road transport	1,662	159.8	638	0.9	1.7	0.3	2.2	18.1
34 Water & rail trans	775	108.1	242	1.0	0.6	0.2	0.6	4.5
35 Air trns, srvcs trns & strg	343	13.1	77	1.2	2.2	0.4	3.0	8.8
36 Communication srvcs	76	8.1	43	0.5	0.6	0.1	0.8	4.5
37 Finance	36	4.1	22	0.5	0.8	0.2	1.0	1.6
38 Insurance	36	3.5	22	0.5	0.7	0.1	1.0	2.3
39 Srvcs to fnnce & invstmnt	62	6.0	39	0.8	1.3	0.3	1.8	5.2
40 Real estate	53	5.7	72	9.9	0.7	0.2	0.8	17.8
41 Ownership OOD	34	3.5	26	8.7	0.8	0.2	1.0	15.1
42 Business srvcs	121	10.9	75	1.3	4.5	0.8	6.1	5.9
43 Central government	168	18.2	78	1.6	2.2	0.4	2.9	21.1
44 Local government	104	12.1	66	3.1	9.9	1.7	13.7	57.6
45 Education	73	10.5	40	1.3	1.3	0.2	1.7	8.0
46 Health & community srvcs	97	13.7	48	1.1	7.9	1.4	11.0	9.0
47 Cultural & rec srvcs	95	10.8	80	4.6	3.5	0.7	4.7	8.8
48 Personal & other comm srvcs	158	18.6	90	5.5	155.7	26.8	217.9	13.8

Note: the same notes apply as for Table 6.8.

Chapter Seven

Extending the Input-Output Frameworks: Ecological Processes and Services in the Auckland Region

In Chapter Seven the input-output framework is extended to cover ecological processes and services in the Auckland Region environmental system (refer to Figure 4.9). To the author's knowledge this is the first time a comprehensive input-output model has been constructed of the ecological processes/services in a region, although the necessity for such an approach has often been identified. For example, Isard's (1968) model includes a Quadrant IV (Ecological System) that essentially depicts such ecological processes in a 'commodity × process' format.

The construction of this extended input-output framework to include ecological processes and services is important for a number of reasons.

- *Structural analysis*. It enables us to understand the ecological processes and services that support human activity and the economy. For example, *structural analysis* is undertaken in this Chapter of the thesis, which enables us to appreciate the direct and indirect flows of ecosystem services that support the economy (refer to Section 7.2).
- *Basis for dynamic modelling*. In this thesis, the static input-output model of ecological processes was the starting point for constructing the system dynamics model of the Earth's environmental system presented in Appendix B.[179]

In this Chapter, first of all (in Section 7.1), an Isard (1968) style input-output model was constructed with processes represented by columns and quantities (or ecological commodities) represented by rows. The inputs of quantities in an Isard (1968) model are signified by negative elements and outputs by positive elements. Next in this Chapter (Section 7.2), an input-output model of ecological service input into each industry in the economy is built and algebraically manipulated to calculate ecological services multipliers (direct plus indirect inputs) for each industry in the economy.

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[179] It was originally intended that a dynamic model of the Auckland Region environmental system would be constructed using the ecological input-output table developed in this Chapter. A severe lack of specific regional data meant this was not possible. A key by-product of this attempt however, was the construction of a novel model of the Earth's biogeochemical cycling. This model, known as the Global Biogeochemical Cycling Model (GBCM) is presented in Appendix B of this thesis.

7.1 Input-Output Model of Ecological Processes in the Auckland Region

7.1.1 Previous Input-Output Models of Ecological Processes

Hannon (1973b) first applied Leontief style input-output analysis to investigate the structure of natural ecosystems. In Hannon's (1973b) paper *The Structure of Ecosystems*, he developed a method for analysing the direct and indirect inputs into ecological processes which was analogous to the well-established method hitherto only used to analyse economic structure. This method was successfully applied to analysing energy flows in the Silver Springs ecosystem in Florida using data collected by Odum (1957).

During the 1970s, Hannon and his colleagues of the University of Illinois further expanded the theoretical and methodological bases of this work. Hannon (1979), for example, used input-output analysis to test the hypothesis that components of ecosystems seek to maximise their total direct and indirect energy storage, and the overall system strives to minimise the metabolised energy per unit of biomass energy. Herendeen (1981), also of the University of Illinois, re-analysed Hannon's (1979) Silver Spring examples, using a new set of assumptions, which resulted in different numerical results in the energy intensities.

Through the 1970s, others also applied input-output analysis to ecological processes and systems. Patten *et al.* (1976) combined input-output analysis and general systems theory to extend the idea of the ecological niche to include indirect effects. Barber (1978) highlighted the probabilistic nature of ecological transfers and the Markovian assumptions that underlie the Leontief input-output approach to ecosystem analysis. Finn (1976) analysed the indirect effects that many ecosystem components exert upon themselves and how to estimate the proportion of total system activity devoted to recycling. Most other studies and certainly those before Costanza *et al.* (1983) covered only one medium, usually energy (heat content) or an elemental flow such as carbon. Implicit in this single medium analysis are the assumptions that all inputs into a system have equal effect and that only one output arises from a process. The latter assumption is particularly problematic as all ecological processes have significant multiple outputs (i.e. joint production).

Costanza *et al.*'s (1983) analysis of the Mississippi Deltaic Plain ecosystems represents the most comprehensive ecological application of input-output analysis. Input-output models of energy and mass flows of 20 different types of ecosystems and 7 hydrological systems were constructed. As well as constructing input-output matrices of each of these systems, Costanza *et al.* (1983) visually depict these systems using Odum's (1971) energy circuit symbols.

Costanza *et al.*'s (1983) work represents an important advance in input-output analysis of ecosystems. Firstly, as previously noted, each of Costanza *et al.*'s (1983) ecosystem models did not restrict themselves to just one element or energy type, but covered a range of elements, compounds and energy types. Secondly, Costanza *et al.* (1983) used a **V** matrix to represent inputs into each process and a **U** matrix to represent outputs.[180] This enables individual processes to have multiple (joint) outputs. In matrix notation, all processes of the ecosystem could be represented by:

$$\mathbf{E} = \varepsilon\mathbf{U} - \varepsilon\mathbf{V}^{t} \quad (7.1)$$

where: **E** is a column vector ($m \times 1$) of direct solar inputs into each process, **V** a matrix ($m \times n$) of inputs into each process, **U** a matrix ($m \times n$) of outputs into each process, and ε a vector ($n \times 1$) of embodied solar inputs into each process.

One of the problems with this system represented by Equation 7.1, is that the joint production (multiple outputs) often results in negative elements occurring in the 'ecological multiplier' ε, which makes little conceptual sense. Subsequent work by Costanza and Neill (1984) attempted to overcome this problem by applying 'non-negativity' constraints within a linear programming framework in order to avoid negative elements in the solution vector ε.

Most of the input-output analysis applied to ecological processes has been at the *ecosystem scale*. To the author's knowledge, no such analysis has been carried out at the *regional or national scale*. Costanza and Neill (1984) did however construct an input-output model of the biosphere. This input-output model was highly aggregative, consisting of 10 commodities (quantities) and 9 processes. They used this model to calculate the embodied solar energy in various commodities such as fresh water, nitrogen and agricultural products. Patterson (2002a) constructed a similar input-output model (16 quantities $\times$ 16 processes), for the purposes of calculating the 'ecological prices' (shadow prices) of various quantities. Patterson (2005) has also constructed a much more detailed input-output model (80 quantities $\times$ 120 processes) of ecological processes in the biosphere, which has also been used to calculate ecological prices.

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[180] Note that these matrices are analogous to the **U** and **V** matrices of Table 4.1, but applied to ecological rather than economic inputs and outputs.

7.1.2 Scope of the Auckland Region Input-Output Model of Ecological Processes

An input-output model of approximately 80 ecological (biogeochemical) processes in the Auckland Region is constructed – refer to Appendix B for further details. This input-output model is a 'quantity × process' model, with outputs represented by **U** and inputs represented by **V**. It is therefore similar, but not identical, to the structure of Costanza's *et al.*'s (1983) model in that it allows for multiple inputs and outputs per process by the use of the **V** and **U** matrices. It differs from the Costanza *et al.* (1983) model in that it has more processes than quantities; leading to an overdetermined system of equations.

It is very important to note this ecological input-output model is only a tentative prototype. It is based on scaling down global data on the ecological processes from Patterson (2005) – refer to Table 7.1. In most cases land and sea areas were used as the scalars, which can only lead to indicative results – it assumes, for example, that the primary productivity per hectare (photosynthesis) in Auckland Region equals the global mean. Although the data is indicative, the actual construction of an operational input-output model of ecological processes both demonstrates the utility of such an approach and represents to the author's knowledge the first attempt to construct such a model at *a regional level*.

Table 7.1 World to Auckland Region Scalars Used to Generate the Prototype Input Output Model of Ecological Processes in the Auckland Region

Processes	Scalar Description	Units	World	New Zealand	Auckland Region	World to New Zealand Scalar	New Zealand to Auckland Region Scalar	World to Auckland Region Scalar
						%	%	%
Carbon Cycle								
oxidation of land humus	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
volcanic action	Random 1:1000 years	N/A	N/A	N/A	0.00	0.0000	0.0000	0.0000
land plant respiration	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
tropospheric oxidation of CO	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
release of CO2	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
absorption of CO2	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
gross land production	Solar radiation onto land[4]	EJ	235,704.00	1,359.47	28.73	0.5768	2.1131	0.0122
production of CO	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
oxidation of CH4	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
sorption of CO	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
production of CH4	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0 1795	1.9432	0.0035
land humus formation (p)	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
land consumption	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
gross marine production	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
marine plant respiration	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
production of CaCO3	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
marine humus formation (p)	Sea Area[1,2]	mil ha	36,130.00	13.95	1 11	0.0386	7.9518	0.0031
marine consumption	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
land humus formation (c&d)	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
marine humus formation (c&d)	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
coal formation	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0 1795	1.9432	0.0035
transfer of land humus	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
oxidation of marine humus	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
kerogen formation	N/A	N/A	N/A	0.00	0 00	0.0000	0.0000	0.0000
formation of limestone	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7 9518	0.0031
weathering of limestone	LRI[8]	ha	N/A	48,300.60	2,090.86	0.1795	4.3288	0.0078
igneous rock formation	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
Hydrological Cycle								
transpiration	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
evaporation from ocean	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
precipitation to ocean	Precipitation[4,5]	m	11,936,340.00	25,678.36	1,600.99	0.2151	6.2348	0.0134
precipitation to land	Precipitation[4,5]	m	3,481,920.00	49,166.65	749.11	1.4121	1.5236	0.0215
evaporation from land	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
uptake of H2O	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
photooxidation of H2	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
river discharge	Water flow into sea	tonnes	N/A	N/A	0.00	0.0000	0.0000	0.0000
Phosphorus Cycle								
weathering of sedimentary P rock	LRI[8]	mil ha	N/A	2.98	0.31	0.1795	10.4324	0.0187
soil to ocean P sediments	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
P runoff	Land Area[6,7]	mil ha	8,451.60	16.33	0.24	0.1932	1.4633	0.0028
evaporation of soluable P	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
deposition of soluable P	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
deposition of insoluable P	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
P particulate flux	N/A	N/A	N/A	N/A	0.00	0.0000	0.0000	0.0000
formation of atmospheric P dust particles	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
dissolution of atmospheric P dust particles	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
P sedimentation	N/A	N/A	N/A	N/A	0.00	0.0000	0.0000	0.0000
sedimentary P rock formation	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031

Notes:
1. Statistics New Zealand (1996)
2. Tennet (1993)
4. Leathwick and Stephens (1998)
5. Huffman *et al.* (1997)
6. Ministry for the Environment (1998)
7. FAO (1998)
8. Landcare Research (2002)

Table 7.1 World to Auckland Region Scalars Used to Generate the Prototype Input Output Model of Ecological Processes in the Auckland Region (Continued)

Processes	Scalar Description	Units	World	New Zealand	Auckland Region	World to New Zealand Scalar	New Zealand to Auckland Region Scalar	World to Auckland Region Scalar
						%	%	%
Sulphur Cycle								
release of H2S	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
ocean spray of SO4	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
uptake of SO2 by ocean	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
uptake of SO2 by soil	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
ocean spray to land	Coastal length[1,3]	km	1,634,701.00	17,230.00	2,360.00	1.0540	13.6970	0.1444
S runoff	Non-Agricultural Land Area[6,7]	mil ha	8,451.60	16.33	0.24	0.1932	1.4633	0.0028
S sedimentation	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
sedimentary S rock formation	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
uplift and weathering of sedimentary S rock	LRI[8]	mil ha	N/A	2.98	0.31	0.1795	10.4324	0.0187
H2S dissolution	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
Nitrogen Cycle								
reduction of N2O	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
oxidation of N2	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
marine dentrification	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
NOx formation by lightning	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
biological fixation by phytoplankton	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
release of N2 and N2O	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
microbial production of N2 and N2O	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
uptake of N2 and N2O	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
photochemical oxidation of N2O	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
wet deposition of NOx	Total Area[1,2]	mil ha	51,010.00	41.17	1.63	0.0807	3.9553	0.0032
acid rain	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
microbial production of NH3	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
uptake of NH3 by soil	Land Area[1,2]	mil ha	14,880.00	26.71	0.52	0.1795	1.9432	0.0035
uptake of NH3 by ocean	Sea Area[1,2]	mil ha	36,130.00	13.95	1.11	0.0386	7.9518	0.0031
N runoff	Non-Agricultural Land Area[6,7]	mil ha	8,451.60	16.33	0.24	0.1932	1.4633	0.0028
sedimentary N rock formation	Sea Area[1,2]	mil ha	36,130.00	26.71	0.52	0.0739	1.9432	0.0014
weathering of sedimentary N rock	LRI[8]	mil ha	N/A	2.98	0.31	0.1795	10.4324	0.0187

Notes:
1. Statistics New Zealand (1996)
2. Tennet (1993)
3. Pruett and Cimino (2000)
6. Ministry for the Environment (1998)
7. FAO (1998)
8. Landcare Research (2002)

The structure of the Auckland Region input-output model of ecological processes is depicted by Figure 7.1. The main structural features of this input-output model (matrix) are: (1) it consists of a '**U** - **V**' matrix of the type first used by Costanza *et al.* (1983), although as previously mentioned there are more processes than quantities ($m > n$); (2) the '**U** - **V**' matrix structure means that inputs are represented by negatives and outputs by positives, unlike the Leontief formulation; (3) the column totals represent the net outputs or net inputs from the Auckland Region system, enabling us to determine whether there is a flow of a particular quantity across the systems boundary and in what direction; (4) the row totals (with respect to energy and mass) should be zero if there is energy mass balance in a process, as there must be according to First Law of Thermodynamics and the Mass Conservation principle (refer to Chapter 2). That is, the mass of reactants must equal the mass of the products for each of the biogeochemical processes in the input-output model – refer to Appendix B; and (5) unlike many biogeochemical models, the biogeochemical cycles (carbon, hydrogen, phosphorus, sulphur and nitrogen) are coupled and interdependent as invariably at least one of the reactants and/or products is from different cycles.

		Quantities									
		Carbon Compounds	...	Phosphorus Compounds	...	Sulphur Compounds	...	Nitrogen Compounds	...	Water	Energy
Processes	*Carbon Cycle* oxidation of land humus volcanic action land plant respiration ⋮ formation of limestone weathering of limestone igneous rock formation										
	Phosphorus Cycle weathering of sedimentary P rock soil to ocean P sediments P runoff ⋮ dissolution of atmospheric P dust particles P sedimentation sedimentary P rock formation										
	Sulphur Cycle release of H2S ocean spray of SO4 uptake of SO2 by ocean ⋮ sedimentary S rock formation uplift and weathering of sedimentary S rock H2S dissolution										
	Nitrogen Cycle reduction of N2O oxidation of N2 marine dentrification ⋮ N runoff sedimentary N rock formation weathering of sedimentary N rock										
	Hydrological Cycle transpiration evaporation from ocean precipitation to ocean ⋮ uptake of H2O photooxidation of H2 river discharge										
	Net Input/Output[2]										

Figure 7.1 Structure of the U - V Matrix of Ecological Flows in the Auckland Region. In the matrix, a negative represents a process input, and a positive represents a process output. A column total represents the net input or output into Auckland Region in the reference year.

For ease of presentation, even though each cycle is connected with the others, there is a separate treatment for each of the five major cycles in Sections 7.1.3 to 7.1.7 of this thesis. Each cycle, as outlined in these Sections, is accompanied by a diagrammatic (Figures 7.2 to 7.6) and a numerical representation (Tables 7.2 to 7.6). In the Figures, the arrows represent processes and the rectangular boxes represent quantities. Each Table describes a biogeochemical cycle in a numerical format which is compatible with the accompanying Figure for that cycle. As Table elements are expressed in net terms (i.e. outputs – inputs) it is possible that a Table cell may appear blank, but in fact be populated with input and output values that cancel each other out. Mass balance is reported in the Table row labelled 'Total'; as inputs must equate to outputs this will be zero. The Figures and the Tables differ in one further respect: the values in the Figures represent only the fluxes of the 'marker' element (refer to Appendix B for further details), while the values in the Tables represent total mass flux.

7.1.3 Auckland Region Carbon Cycle Module

The carbon cycle for the Auckland Region is depicted by Figure 7.2. Table 7.2 describes the total elemental fluxes of the carbon cycle in a numerical format which is compatible with that outlined by Figure 7.2.

Slow Carbon Cycle

Biogeochemists such as Bolin *et al.* (1979), Revelle (1982), Degen *et al.* (1984), Schlesinger (1991) and Holman (1992) have separated the carbon cycle into slow and fast sub-components. The slow carbon cycle is primarily inorganically controlled. Reservoirs of sedimentary rocks, such as limestone or calcite, are augmented through a series of processes that convert CO_2 released into the atmosphere ultimately into sedimentary rock. Dissolved calcium, magnesium and bicarbonate ions are transported via freshwater systems to the oceans (Ayres, 1992, 1996), and are precipitated through ocean layers or extracted and temporarily incorporated by marine organisms into their skeletons or shells. Over time the inorganic precipitates and shells/skeletons, comprising 34 kt C per year in the Auckland Region, settle on the ocean floor as sediments and, under pressure, utilising 11 kt C, are converted to sedimentary rocks. In reverse, the carbon in the sedimentary rocks may be released through volcanic action or tectonic uplift and, once again over time, broken down, releasing 27 kt of C per year through chemical weathering. The geochemical processes of the slow carbon cycle are however too slow to account for the hypothesised relationship between CO_2 production and global warming.

Fast Carbon Cycle

The fast carbon cycle is mainly controlled by biological processes – it also incorporates the largest carbon fluxes. Through the process of photosynthesis, CO_2 is biologically transformed into carbohydrates i.e. gross land/marine production, utilising an estimated[181] 17,368 kt C and 1,252 kt C respectively. Operating in reverse is the aerobic process of land/marine respiration, releasing 3,139 kt C and 368 kt C respectively.[182] Photosynthesis, and sorption by the ocean of 2,171 kt C, are the major processes involved in removing CO_2 from the atmosphere.[183] Other lesser land-based fluxes include soil humus formation, partially by way of consumption of land producers[184], utilising 1,573 kt C. Subsequent oxidation of soil humus releases CO_2 containing 1,402 kt C into the atmosphere. Soil humus may also be transferred by freshwater systems to the ocean and accounts for 12 kt C. Similarly, lesser marine-based fluxes encompass marine plant consumption of 12 kt C, formation of marine biomass accounting for 8 kt C (consumers and decomposers) and 724 kt C (producers), and in turn, its oxidation, releasing 645 kt C. Of course, the fast carbon cycle is not solely limited to these fluxes. A small reservoir of organic carbon exists in kerogen, which through heat, geological and biological processes is transformed into coal (0.26 kt C), oil shale and petroleum (Ayres, 1996; Smil, 2002). Human combustion of fossil fuels is primarily responsible for the re-release of atmospheric CO_2 from these sources.

[181] As discussed in Section 7.1.2, all the data in Sections 7.1.3 – 7.1.7 are crude estimates based on scaling down global data to the regional level. Therefore, all the numbers quoted in these Sections of the text should be treated as such, even though the author has desisted from explicitly stating this for the sake of brevity.

[182] The net product of gross production and respiration is referred to as net photosynthesis, while net photosynthesis less respiration of non-photosynthetic plants is known as 'net primary production' (den Elzen *et al.*, 1995; Ayres, 1996).

[183] Atmospheric CO_2 content exhibits a significant seasonal oscillation, due mainly to differences in (1) the uptake of CO_2 by producers, and (2) human combustion of fossil fuels.

[184] Consumers and decomposers typically have a combined biomass of less than 1 percent of producers, but are able to reoxidise more than 99 percent of net primary production into CO_2 or bicarbonates (den Elzen *et al.*, 1995; Ayres, 1996).

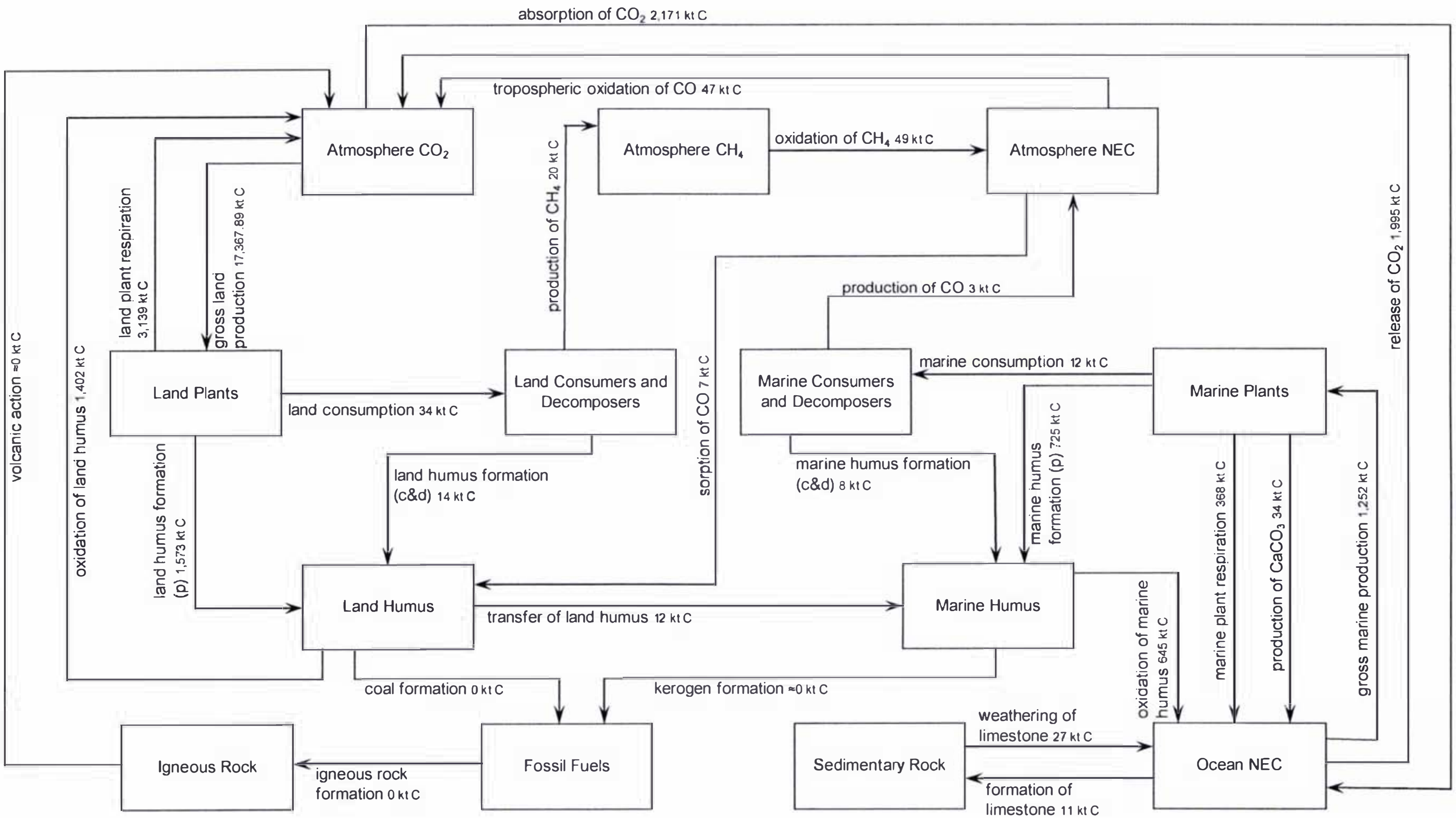

Figure 7.2 **Auckland Region's Carbon Cycle, 1997-98**

Table 7.2 Input-Output Model of the Carbon Cycle Processes for Auckland Region, 1997-98

	units	*Carbon Processes* oxidation of land humus	volcanic action	land plant respiration	tropospheric oxidation of CO	release of CO_2	absorption of CO_2	gross land production	production of CO	oxidation of CH_4	sorption of CO	production of CH_4	land humus formation (p)	land consumption
Carbon Compounds														
Land Humus	kt	-3,038 [1]									14		2,727	
Igneous Rock	kt													
Land Plants	kt			-7,977				44,133					-3,997	-85
Carbon Monoxide	kt				-110				8	115	-15			
Hydrogen carbonate	kt					-10,138	11,029							
Carbon Dioxide	kt	5,137		11,504	173	7,312	-7,955	-63,644				29	1,153	
Marine Biota	kt								-11					
Methane	kt									-66		16		
Land Biota	kt											-39		66
Marine Plants	kt													
Marine Humus	kt													
Calcium carbonate	kt													
Sedimentary Rock	kt													
Coal	kt													
Other														
Water	kt	1,314		4,709		2,993	-3,256	-26,053	6	148	-6	-15	1,180	
Oxygen	kt	-3,772		-8,727	-63			48,281	-6	-197	9	1	-986	53
Other	kt	359		491		-167	182	-2,717	3		-2	8	-77	-34
Total	kt													
Energy														

Notes:
1. In the matrix, a negative represents a process input and a positive represents a process output.
2. Solar energy inputs.

Table 7.2 Input-Output Model of the Carbon Cycle Processes for Auckland Region, 1997-98 (Continued)

Carbon Processes	units	gross marine production	marine plant respiration	production of $CaCO_3$	marine humus formation (p)	marine consumption	land humus formation (c&d)	marine humus formation (c&d)	coal formation	transfer of land humus	oxidation of marine humus	kerogen formation	formation of limestone	weathering of limestone	igneous rock formation
Carbon Compounds															
Land Humus	kt						24		-1	-27					
Igneous Rock	kt														0
Land Plants	kt														
Carbon Monoxide	kt								0						
Hydrogen carbonate	kt	-6,359	1,872								3,275			138	
Carbon Dioxide	kt						10								0
Marine Biota	kt					39		-27							
Methane	kt														
Land Biota	kt						-28								
Marine Plants	kt	2,867	-844	-77	-1,660	-27									
Marine Humus	kt				1,633			19		28	-1,453				
Calcium carbonate	kt			281										-227	
Sedimentary Rock	kt														0
Coal	kt								0						
Other															
Water	kt	-469	138	38	163	-9	10	8	0	0	-1,006				
Oxygen	kt	4,418	-1,301	-142	-174	4	-31	-5	0	-1	-1,031				0
Other	kt	-458	135	-100	37	-7	13	6	0	-1	214			88	0
Total	kt														
Energy		(2)													

The fast carbon cycle is also characterised by the methane sub-cycle. The atmospheric reservoirs of CH_4 and CO are incorporated here. Removal of CH_4 from the atmosphere involves (1) oxidation by hydroxyl to carbon monoxide, which is subsequently oxidised to CO_2, utilising 49 kt C, and (2) soil uptake (Bowen, 1979), accounting for 7.0 kt C. Methane is produced by land consumers during microbial organic decomposition through methanogenesis, a complicated and temperature dependent series of sub-processes (Thompson and Cicerone, 1986; Schlesinger, 1991; Holman, 1992). Such biogenic methane sources include natural wetlands, ruminants[185], biomass burning, landfills and solid waste dumps. Non-biogenic sources include crustal vents and coal mines. Methane like CO_2 is a greenhouse gas, but in relative terms is significantly more potent – each molecule contributes 20 times that of a CO_2 equivalent (Lashof and Ahuja, 1990).

7.1.4 Auckland Region Hydrological Cycle Module

The hydrological cycle module for the Auckland Region is depicted diagrammatically in Figure 7.3, while the total elemental fluxes are described in numerical format in Table 7.3.

The circulation of water (H_2O) represents the largest mass flux occurring in the Auckland Region. Through the process of evaporation, precipitation and transpiration, H_2O transfers much of the heat received in the region's annual solar flux. These transfers are paramount in determining the climatic patterns of the region and the level of net primary production across the region's terrestrial area.[186] Atmospheric H_2O is primarily acquired by oceanic evaporation, which releases 1,320 Mt H per year in the Auckland Region, although lesser contributions of 105 Mt H and 140 Mt H are made by land producer transpiration and evaporation of freshwater respectively. When precipitation to land (2,368 Mt H) exceeds evaporation, runoff into stream/river systems will occur, and ultimately discharge into the ocean.[187] Precipitation directly into the ocean contains 5,231 Mt H. Freshwater may also be taken up by plants, accounting for 105 Mt H annually. In the atmosphere dihydrogen may be photo-oxidised by solar radiation to form atmospheric H_2O, involving a flux of 0.13 Mt H. Dihydrogen is also one of the few molecules that can be directly lost to space (Bowen, 1979).

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[185] Animal waste and excrement.

[186] Through precipitation the atmosphere is cleansed of particulate matter and soluble trace gases (Likens and Borman, 1974).

[187] Runoff and river discharge play a critical role in transporting the products of weathering to the ocean. They are conventionally studied using box diffusion models (Waring *et al*., 1981) in which water inputs and outputs must balance across each box, any loss of water being determined by gradient or vapour pressure deficit between plant foliage and the atmosphere.

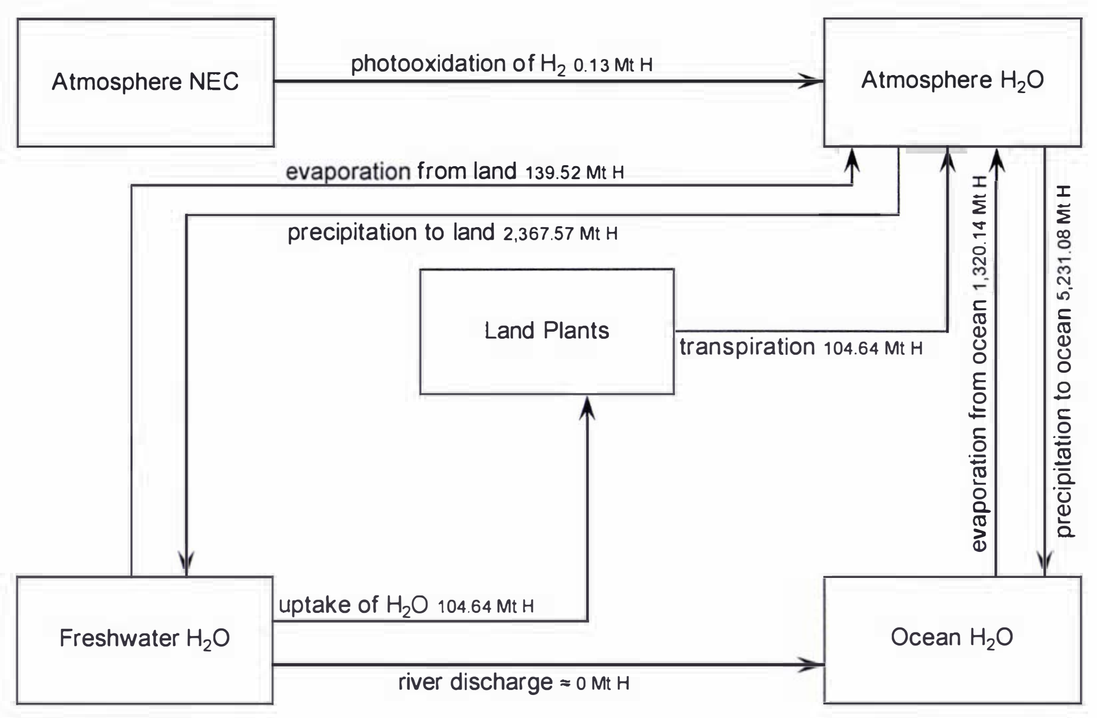

Figure 7.3 Auckland Region's Hydrological Cycle, 1997-98

Table 7.3 Input-Output Model of the Hydrological Cycle Processes for Auckland Region, 1997-98

		Hydrological Processes							
	units	transpiration	evaporation from ocean	precipitation to ocean	precipitation to land	evaporation from land	uptake of H_2O	photooxidation of H_2	river discharge
Hydrological Compounds									
Water	Mt	(1)		1.14					
Hydrogen (Atmosphere)	Mt								
Hydrogen	Mt			-0.13					
Hydroxide	Mt								
Other									
Oxygen	Mt			-1.01					
Other	Mt								
Total	Mt								
Energy		(2)	(2)	(2)	(2)	(2)		(2)	(2)

Note: the same notes apply as for Table 7.2.

7.1.5 Auckland Region Phosphorus Cycle Module

The phosphorus cycle module for the Auckland Region is depicted in Figure 7.4 with total elemental flux described in numerical format in Table 7.4.

Phosphorous is another important element playing an essential role in many biogeochemical processes. Phosphorous, like nitrogen, is a key limiting factor in terrestrial and oceanic plant growth. Controversy exists as to which of P or N is the more limiting factor, particularly in the ocean. Jahnke (1992) argues that in the long term P is more likely to be the limiting factor – if only because the atmosphere contains an abundant supply of N for marine fixation. Previous studies of the global P cycle have included Stumm (1973), Lerman *et al.* (1975), Schlesinger (1991), Wollast *et al.* (1993), den Elzen *et al.* (1995), Tiessen (1995) and Smil (2000, 2002).

The phosphorous cycle is unique among the cycles presented here for two reasons, and this is demonstrated in the Auckland Region input output model.[188] Firstly, the P cycle lacks any gaseous fluxes (Jahnke, 1992; den Elzen *et al.*, 1995; Smil, 2002). The atmosphere plays a relatively minor role in P transportation in dust particles, seaspray, rain and cloud droplets (Jahnke, 1992). In the Auckland Region this includes formation of atmospheric dust particles containing 0.10 kt P, dissolution of these particles to soil releasing 0.07 kt P, deposition of 0.02 kt of soluble P in the surface ocean and, in reverse, evaporation of 0.01 kt of soluble P by the atmosphere, and the deposition of 0.02 kt of insoluble P to sediments. Secondly, microbial and oxidation-reduction reactions are of little influence in controlling the distribution of P terrestrially, i.e. P cycling is largely inorganic in nature (Jahnke, 1992). Weathering and transportation of calcium phosphate rock, particularly apatite $Ca_5(PO_4)_3OH$, is instead the major terrestrial flux (Mackenzie *et al.*, 1993; Tiessen, 1995; Smil, 2000), releasing 4.01 kt P into Auckland Region soils. Transportation of 0.65 kt P is typically through stream/river transfer of soil to marine sediment. Oceanic upwelling and downwelling also transports P, with eventual deposition as sediment. Over geological time sedimentary rocks are formed by compaction, pressure and heat, accounting for 0.66 kt P.

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[188] A possible third reason is that the estimation of natural P fluxes is extremely difficult (Schlesinger, 1991; Jahnke, 1992; den Elzen *et al.*, 1995). There are primarily two reasons for this: (1) P is mostly present in particulate, rather than biological, form, and (2) the introduction of P from anthropogenic sources obscures natural fluxes.

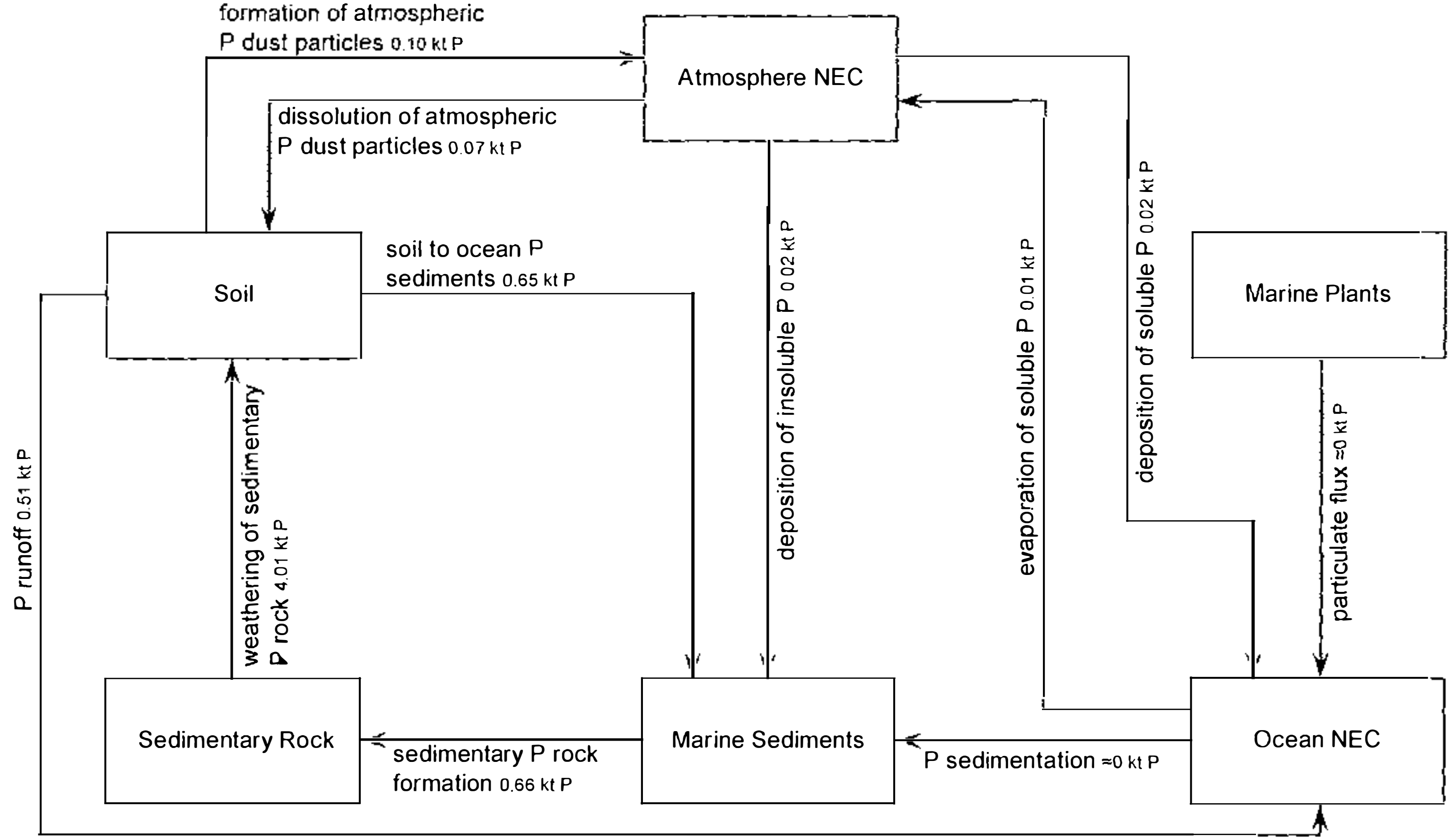

Figure 7.4 Auckland Region's Phosphorus Cycle, 1997-98

Table 7.4 Input-Output Model of the Phosphorus Cycle Processes for Auckland Region, 1997-98

	units	*Phosphorus Processes* weathering of sedimentary P rock	soil to ocean P sediments	P runoff	evaporation of soluable P	deposition of soluable P	deposition of insoluable P	P particulate flux	formation of atmospheric P dust particles	dissolution of atmospheric P dust particles	P sedimentation	sedimentary P rock formation
Phosphorus Compounds												
Calcium phosphate	kt	0.05	-0.08			0.53	-0.36					
Phosphate	kt					-0.30	0.21					
Monohydrogen phosphate	kt	-0.03 (1)	0.05									
Other												
Water	kt	0.00	-0.01									
Oxygen	kt											
Other	kt	-0.03	0.04			-0.23	0.16					
Total	kt											

Note: the same notes apply as for Table 7.2.

7.1.6 Auckland Region Sulphur Cycle Module

The Auckland Region sulphur cycle module is depicted in diagrammatic format in Figure 7.5, while the accompanying Table 7.5 represents total elemental flux for the sulphur cycle in numerical.

Sulphur is a key nutrient to life providing structural integrity to protein-based tissue (Charlson *et al.*, 1992a). In its fully oxidised state sulphur exists as sulphate, SO_4^{2-}, an abundant anion in both freshwater and seawater. Sulphate is the major cause of acidity in rainwater, and consequently plays a fundamental role in chemical weathering, often in the form of acid rain. The S cycle has been studied extensively by *inter alia* Freney *et al.* (1983), Galloway (1985), Schlesinger (1991), Charlson *et al.* (1992a, 1992b), Mackenzie *et al.* (1993), Wollast *et al.* (1993), Jones *et al.* (1994), den Elzen *et al.* (1995), Ayres (1996) and Smil (2002).

Figure 7.5 depicts the major annual fluxes of the S cycle in the Auckland Region. Significant fluxes of S entering the atmosphere are the release of H_2S by marine plants containing 1.69 kt S, and sea spray containing 1.35 kt S, which is promptly deposited onto land. Bigg *et al.* (1984) have identified sulphate as the dominant component of cloud condensing nuclei (CCN) – which is postulated to have a significant impact on global radiation.[189] Biological processes result in the release of reduced gases to the atmosphere. Ocean-based emissions are typically of dimethylsulphide (CH_3SCH_3 or 'DMS') and carbonyl sulphide (COS)[190] from the reduction of seawater sulphate by phytoplankton, while hydrogen sulphide (H_2S) is emitted by terrestrial soils and plants. Sulphates in soil and seawater are taken up by plants and then reduced to organic sulphur compounds (e.g. amino acids such as cysteine). Decaying matter retains some S, but is mostly converted to H_2S by decomposers. Volcanism may also sporadically inject sulphate into the atmosphere.

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[189] Charlson *et al.* (1987, 1992a), *inter alia*, have at the global level proposed the existence of a homeostatic feedback loop which may regulate the Earth's climate. Charlson *et al.* (1987) point out that because cloud albedo is partially a function of CCN density, any increase in atmospheric S may lead to greater cloud cover, reducing solar radiation, and lowering phytoplankton photosynthesis. Consequently, lowering phytoplankton photosynthesis lessens the amount of CCN and, in turn, increases solar radiation. Watson and Liss (1998) and Smil (2002) are however sceptical of this homeostatic climate control, questioning both its magnitude and direction.

[190] COS is the most abundant atmospheric species in the troposphere. Because of its inert chemical behaviour, and consequently long residence time, it may enter the stratosphere. In turn, it may be photochemically oxidised to sulphate (Mackenzie *et al.*, 1993)

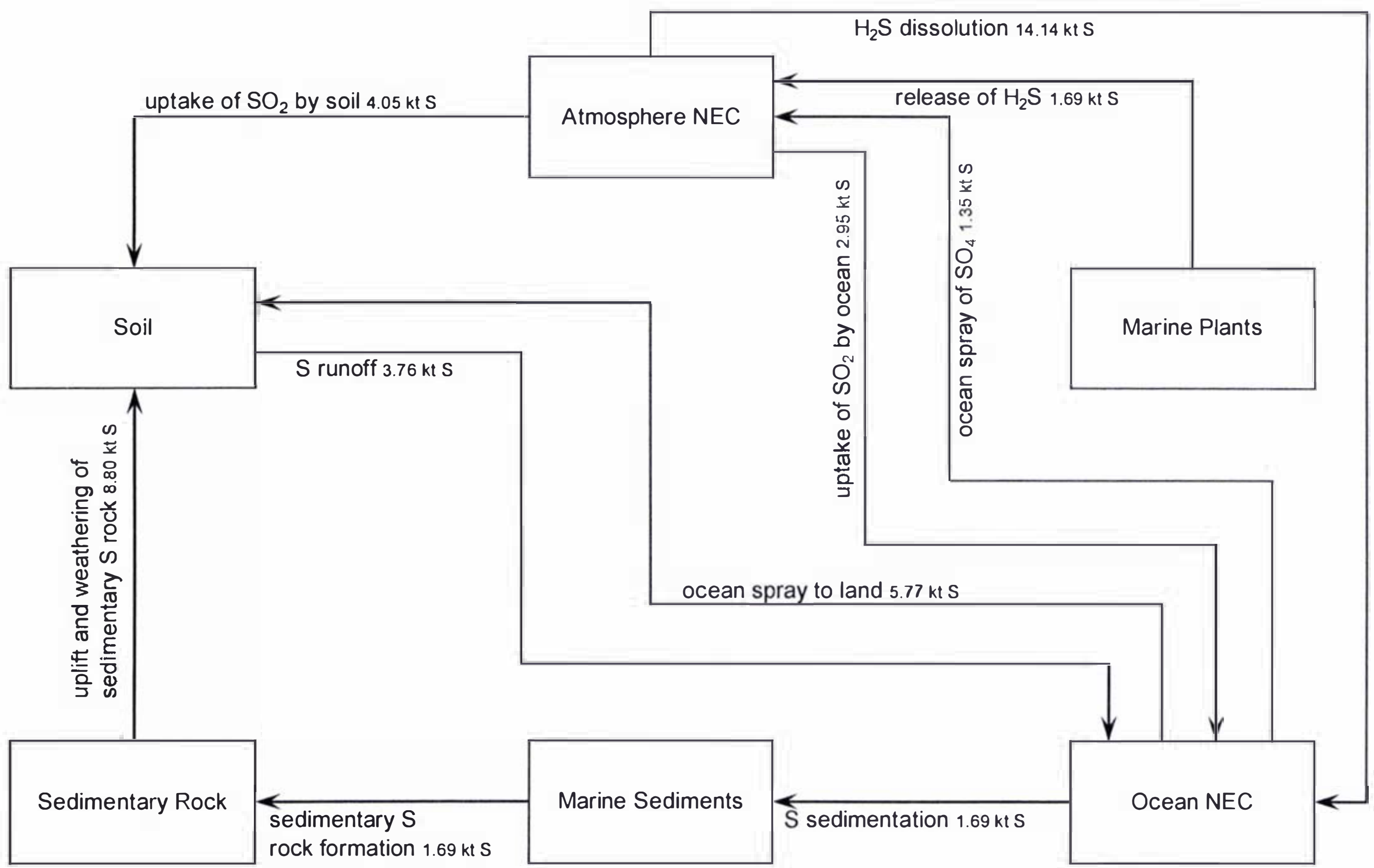

Figure 7.5 Auckland Region's Sulphur Cycle, 1997-98

Significant sources of S in soil are obtained from uptake of SO_2 containing 4.05 kt S, ocean spray depositing 5.77 kt S onto land, and uplift and weathering of sedimentary S rock, supplying 8.80 kt S per year to soil in the Auckland Region. Transportation of soil via runoff accounts for 3.76 kt of S entering the ocean, with 1.69 kt S per year undergoing sedimentation to form S rock. Two further notable fluxes of S into the ocean are H_2S dissolution releasing 14.14 kt S, and oceanic uptake of SO_2, accounting for 2.95 kt S.

The cycling of sulphur from gas to sulphate particles and subsequent wet deposition (via rainwater) on the Earth's surface is a rapid process. The impacts of the atmospheric S cycle are thus typically localised or regional, with most S being distributed close to its source. Moreover, the S cycle is arguably the most perturbed by human activity of all the cycles through mainly fossil fuel combustion and biomass burning, with anthropogenic emissions equating to 40 percent of total surface-atmosphere flux (Andreae, 1985). The most common manifestation of this perturbation is acid rain – an event that is best studied on a regional basis.[191]

Table 7.5 Input-Output Model of the Sulphur Cycle Processes for Auckland Region, 1997-98

		Sulphur Processes									
	units	release of H_2S	ocean spray of SO_4	uptake of SO_2 by ocean	uptake of SO_2 by soil	ocean spray to land	S runoff	S sedimentation	sedimentary S rock formation	uplift and weathering of sedimentary S rock	H_2S dissolution
Sulphur Compounds											
Hydrogen sulphide	kt								-15.0		
Sulphate	kt	8.8	12.1				-5.1	26.4	42.4		
Sulphur dioxide	kt	-5.9 (1)	-8.1								
Sulphur	kt						1.7	-8.8			
Other											
Water	kt								-31.8		
Oxygen	kt	-2.9	-4.0				3.4	-17.6			
Other	kt								4.4		
Total	kt										

Note: the same notes apply as for Table 7.2.

[191] Charlson *et al.* (1992) and den Elzen *et al.* (1995) note that the calculation of a global S budget requires the painstaking process of a myriad of measurements over a wide range of regions, in turn adjusted for seasonality, to produce reasonable averages.

7.1.7 Auckland Region Nitrogen Cycle Module

The nitrogen cycle module for the Auckland Region is depicted in Figure 7.6 with total elemental fluxes described in numerical format in Table 7.6.

Despite its abundance in the atmosphere, nitrogen is a relatively rare element in the terrestrial biosphere (Soderland and Svenson, 1976; McElroy *et al.*, 1977; Jaffe, 1992; Bart *et al.*, 1993; Wollast *et al.*, 1993; Ayres *et al.*, 1994). The availability of nitrogen is a critical/limiting factor in numerous biogeochemical processes. Nitrogen limits the rate of net primary production (Vitousek and Howarth, 1991), is a critical component in enzymes, hormones, chlorophyll and genes that control biogeochemical reactions that reduce/oxidise carbons (den Elzen *et al.*, 1995), and plays an important role in a number of environmental issues e.g. acidification, surface water pollution/eutrophication, stratospheric ozone depletion, photochemical smog and so on.

Figure 7.6 reveals the complex set of biotic and abiotic fluxes in the Auckland Region that comprise the nitrogen cycle. These processes may be broadly grouped as: (1) organic atmospheric. Denitrification by bacteria (mainly of genus *Rhizobium*) of decaying organic materials and by plants, which release N_2 and N_2O into the atmosphere (i.e. microbial production of inert N_2 and N_2O, producing 8.46 kt N per year), and release of N_2 and N_2O by marine plants, accounting for 1.23 kt N per year. In reverse, biological fixation by bacteria and phytoplankton of 1.23 kt N convert N_2 to NH_3, which is converted in turn through bacterial nitrification to NH_4, and ultimately to nitrites (NO_2) and nitrates (NO_3). Since plants cannot utilise elemental nitrogen, all life therefore depends on biological fixation – not surprisingly 95 percent of all nitrogen fluxes thus involve biological processes (Jaffe, 1992); (2) inorganic atmospheric from *inter alia* the formation of NOx by lightning (0.32 kt N), wet deposition of NO_x (0.48 kt N) and acid rain (0.45 kt N); and (3) oceanic. Weathering and formation of sedimentary rock utilising 0.94 kt N, uptake and oxidation of NH_3 using 4.29 kt N, and receipt of non-agricultural runoff containing 0.90 kt N. The complex nature of the nitrogen cycle means that quantification of these fluxes is still very much in its infancy.

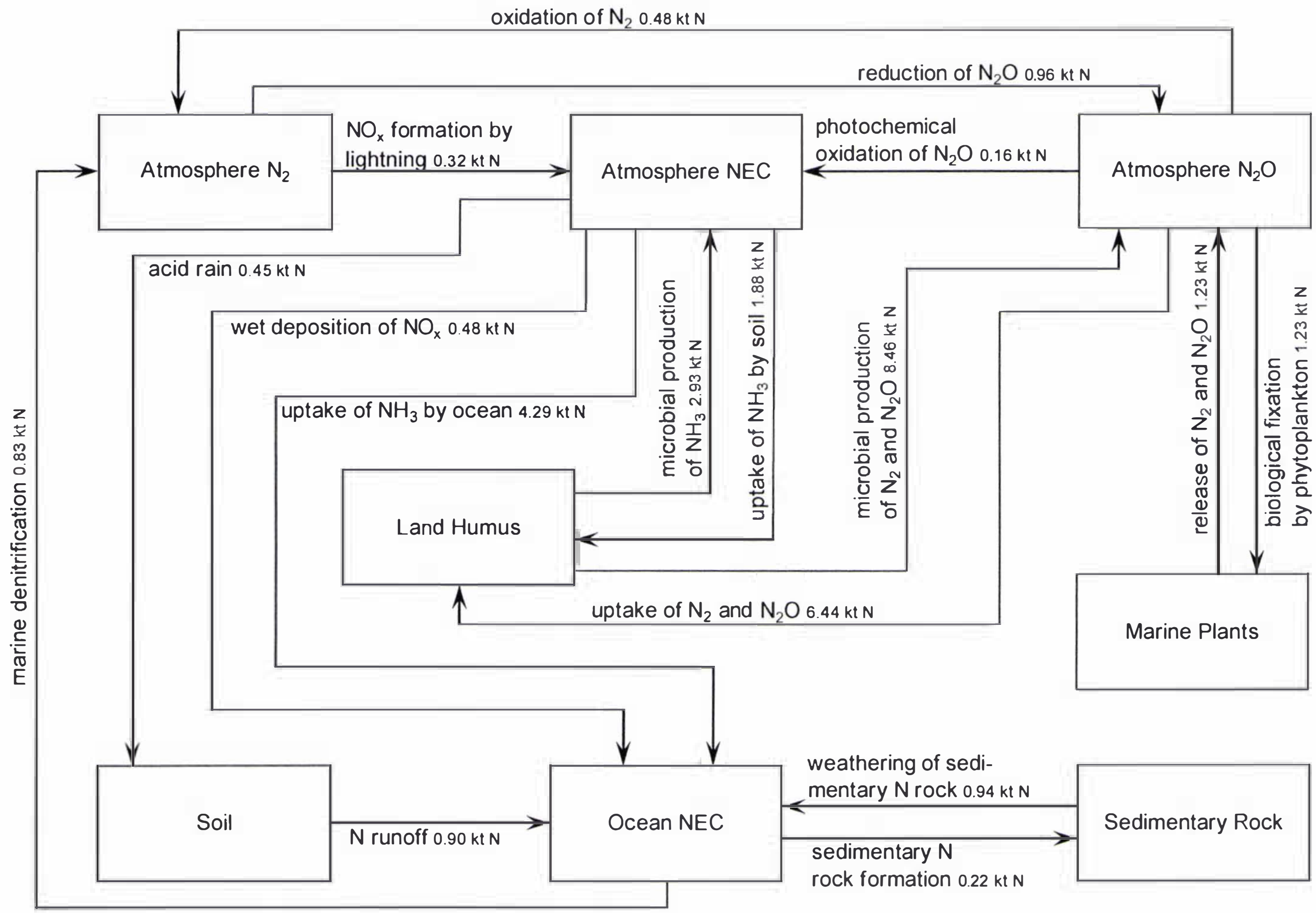

Figure 7.6 Auckland Region's Nitrogen Cycle, 1997-98

Table 7.6 Input-Output Model of the Nitrogen Cycle Processes for Auckland Region, 1997-98

	units	*Nitrogen Processes* reduction of N_2O	oxidation of N_2	marine dentrification	NO_x formation by lightning	biological fixation by phytoplankton	release of N_2 and N_2O	microbial production of N_2 and N_2O	uptake of N_2 and N_2O	photochemical oxidation of N_2O	wet deposition of NO_x	acid rain	microbial production of NH_3	uptake of NH_3 by soil	uptake of NH_3 by ocean	N runoff	sedimentary N rock formation	weathering of sedimentary N rock
Nitrogen Compounds																		
Nitrous oxide	kt	0.8			-0.2	0.2	2.5	-1.9	-0.3									
Nitrogen	kt	-0.5 (1)	0.8	-0.3	-1.1	1.1	6.9	-5.2										
NO_x	kt			0.9					0.4	-1.3	-1.2							
Ammonia	kt											3.6	-2.3					
Nitrate (Soil)	kt										2.0							
Nitrate	kt		-3.7							2.1						-1.0	4.1	
Ammonium	kt															0.3	-1.2	
Other																		
Water	kt		3.2		-29.6	29.6	84.3	-64.2				-42.9	27.6					
Oxygen	kt	-0.3		-0.5	71.3	-71.3	-383.7	292.1	-0.2	-0.8	-0.8					0.7	-3.2	
Other	kt		-0.4		-40.3	40.3	290.0	-220.8				39.3	-25.3			-0.1	0.3	
Total	kt																	
Energy					(2)					(2)								

Note: the same notes apply as for Table 7.2.

The organic atmospheric process of denitrification and biological fixation are heavily perturbed by human activity (Jaffe, 1992; Ayres, 1996). To replenish or introduce nitrogen into soil many agriculturalists plant leguminous plants such as clover and soybeans. The most significant increases in agriculture have however been generated by application of synthetic nitrogen-based fertilisers.[192] Nitrogen is also released into the atmosphere in the form of nitrous oxides from combustion of fossil fuels and by thermal power stations. The effects of these perturbations are currently poorly understood (den Elzen *et al.*, 1995).

7.1.8 Limitations and Caveats

There are several limitations and caveats of the input-output model of ecological processes in the Auckland Region.

- *Closed system.* At present the biogeochemical cycling model records only fluxes that occur within the Auckland Region. Clearly many biogeochemical fluxes cross this system's spatial boundaries – the importance of these fluxes should not be overlooked. For example, CO_2 emissions by other regions and, more importantly, by other nations may have a significant impact on Auckland Region's climate, food production and so on. In Appendix B mass fluxes for global biogeochemical cycling, arguably a true closed system, are also established.
- *Only inflows and outflows are considered in the input-output model.* Fundamentally, input-output models are flow models, meaning that in this model only mass flows (fluxes) are recorded. Stocks of the biogeochemical species are not recorded. However, in Appendix B, both stocks and flows are considered in a dynamic model of Auckland Region's biogeochemical processes. This simultaneous consideration of both stocks and flows provides a better basis for considering some sustainability issues – hence the value of this type of dynamic model.
- *Temporal boundaries.* The model provides a static snapshot of biogeochemical flows in the Auckland Region for only the study year. Almost all biogeochemical processes operate over other time frames, with residence times ranging from nanoseconds to geological time. It can therefore be argued that the estimates generated for the slower parts of cycles are more difficult to interpret in the context of this static model.
- *Data is only broadly indicative.* This is a prototype input-output model of the ecological processes in the Auckland Region. The data is only broadly indicative. It is purely based on scaling down world global data to the Auckland Region, based on land

[192] Synthetically derived nitrogen is also utilised in the manufacture of explosives, pesticides, plastics and so on.

area, sea area and other such data (refer to Table 7.1). As such a number of assumptions are made – for example, it is assumed that for gross land production the mean global land productivity equals mean Auckland Region land productivity. It is beyond the scope and resourcing of this project to improve on this prototype data. It is estimated that it would take several person-years to collate, collect and analyse all of the data required to construct a robust input-output model of ecological processes in Auckland Region. The type of approach used by Costanza *et al.* (1983) for the Mississippi Deltaic Plain Region is a good example of how this could be achieved.

- *No connection with the physical input-output model.* As the input-output model of ecological processes of the environmental system currently stands, it is not connected to the physical input-output model of the economy which was constructed in Chapter 6. This connection via feedbacks in both directions is desirable, so that the structural interdependencies between the physical economy and physical flows in the environmental system can be understood. For example, such an analysis could quantitatively demonstrate how ecological processes directly and indirectly support economic activities. Such connections were not made in this modelling framework due to: (1) practical difficulties in collecting and analysing the required data within the timeframe of a PhD thesis; (2) difficulties in dealing with *spatial scale effects*[193] when pollutants enter the environment or resources are drawn from the environment; and (3) difficulties in dealing with *temporal effects* when there are significant time-lags involved. For example, nitrogen entering the soil (from the physical economy) may take several decades before it filters through the soil/geological system into a nearby lake. Such effects cannot be captured by a static input-output model.

7.2 Input-Output Model of Ecological Services Input into the Auckland Region Economy

In Section 7.1 an input-output model of ecological processes in the Auckland Region was constructed. Another way to view those ecological processes is in terms of the ecosystem services that emerge from these processes, i.e. the ecological services that contribute directly and indirectly to human welfare. Such ecological services include, for example, gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control, soil

[193] There are several types of spatial scale effects that need to be considered: (1) many residuals (pollutants) have only *localised effects* – e.g. nitrogen loadings might affect a stream's water quality (increasing for example the aquatic productivity for that stream, but not all aquatic environments in Auckland Region). It would be very difficult to accommodate such localised spatial effects within an input-output modelling framework, and ideally a GIS component would need to be integrated into the framework to take account of these effects; and (2) many residuals (pollutants) primarily have *global effects* e.g. CO_2 emissions produced globally affect Auckland Region's climate (and consequently ecological processes) far more than CO_2 emissions produced within the Auckland Region.

formation, nutrient recycling, waste treatment, pollination, biological control, refugia, food production, genetic resources and so forth (refer to Table 7.7). The approach used in this Section of the thesis is to quantify those ecological service inputs in monetary terms, following the approach of Costanza *et al.* (1997). Full details on how this data was collected and put into an input-output structure are presented in Appendix J.

The purpose of this Section is to construct an input-output model that shows how ecological services contribute to each industry in the Auckland Region economy. Using this model, an extended form of multiplier analysis will then be used to calculate the direct and indirect ecosystem services embodied in the output of various industries in the Auckland Region economy. This involves developing a tree diagram that depicts exactly where these indirect ecosystem services come from and in what quantities.

Table 7.7 Summary of the Ecosystem Services Assessed

	Ecosystem Service	Definition	Examples
1	Gas regulation	Regulation of atmosphere chemical composition	CO_2/O_2 balance, O_3 for UV protection and SOx levels
2	Climate regulation	Regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels	Greenhouse gas regulation, dimethylsulphate production affecting cloud formation
3	Disturbance regulation	Capacitance, damping, and integrity of ecosystem response to environmental fluctuations	Storm protection, flood control, drought recovery, and other aspects of habitat response to environmental variability mainly controlled by vegetation structure
4	Water regulation	Regulation of hydrological flows	Provisioning of water for agricultural, industrial processes or transportation
5	Water supply	Storage and retention of water	Provisioning of water by watersheds, reservoirs, and aquifers
6	Erosion control and sediment retention	Retention of soil within an ecosystem	Prevention of loss of soil by wind, runoff or other removal processes. Storage of silt in lakes and wetlands
7	Soil formation	Soil formation processes	Weathering of rock and the accumulation of organic material
8	Nutrient cycling	Storage, internal cycling, processing and acquisition of nutrients	N, P and other elemental or nutrient cycles
9	Waste treatment	Recovery of mobile nutrients and removal or breakdown of excess or xenic nutrients and compounds	Waste treatment, pollution control, detoxification
10	Pollination	Movement of floral gametes	Provisioning of pollinators for the reproduction of plant populations
11	Biological control	Trophic-dynamic regulations of populations	Keystone predator control of prey species, reduction of herbivory by top predators
12	Refugia	Habitat for resident and transient populations	Nurseries, habitat for migratory species, regional habitats for locally harvested species or overwintering grounds
13	Food production	That portion of gross primary production extractable as food	Production of animals, fish, fruit and vegetables for human consumption
14	Raw materials	That portion of gross primary production extractable as raw materials	The production of timber, fibres (e.g. wool) or fodder
15	Genetic resources	Sources of unique biological materials and products	Medicine, genes for resistance to plant pathogens and crop pests
16	Recreation	Providing opportunities for recreational activities	Eco-tourism, sport fishing, and other outdoor recreational activities
17	Cultural	Providing opportunities for non-commercial purposes	Aesthetic, artistic, educational, spiritual and/or scientific values of ecosystems

Source: Based on Table 1 from Costanza *et al.* (1997)

7.2.1 Methodology

An input-output model of the structure depicted by Figure 7.7 was developed. This is essentially a standard Leontief industry-by-industry model, augmented with a sub-matrix that quantifies the direct ecosystem services inputs into each industry in the economy.

		Economic Industries						
		1 Horticulture and fruit growing	2 Livestock and cropping farming	3 Dairy cattle farming	…	46 Health and community services	47 Cultural and recreational services	48 Personal and other community services
Economic Industries	1 Horticulture and fruit growing							
	2 Livestock and cropping farming							
	3 Dairy cattle farming							
	⋮							
	46 Health and community services							
	47 Cultural and recreational services							
	48 Personal and other community services							
Ecological Services	1 Gas regulation							
	2 Climate regulation							
	3 Disturbance regulation							
	⋮							
	15 Genetic resources							
	16 Recreation							
	17 Cultural							

Figure 7.7 Input-Output Model Accounting Framework

The methodology used in this Section of the thesis consists of five steps described by Figure 7.8. Steps 1 and 2 are based on Costanza and Neill's (1981) approach to calculating ecological multipliers, while steps 3 to 5 are based on the method developed by Patterson and McDonald (2004) which enables a tree diagram to be developed that pictorially decomposes the ecological multiplier into its component parts (by round).

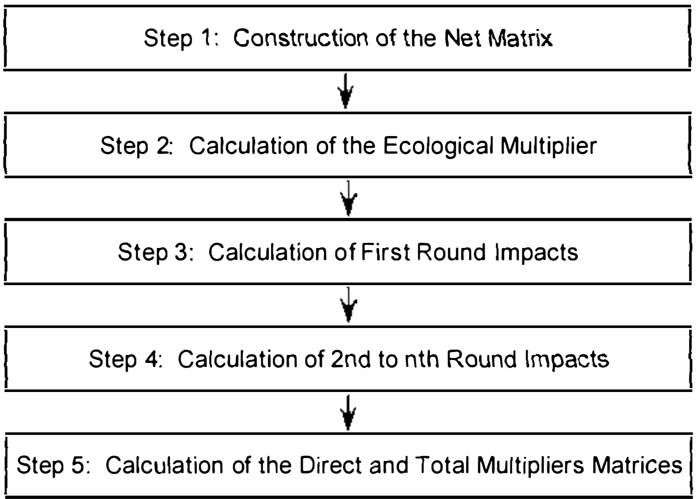

Figure 7.8 Methodological Process for Calculating Ecological Multipliers and Tree Diagrams

Step 1 Construction of the Net Matrix

A 'net matrix' is constructed from a standard industry-by-industry input-output table (**Aβ** = **ф**).[194] The net matrix is defined as **Ђ** - **Љ**, where the matrix **Љ** (Γ x B) is set equivalent to the **Aβ** matrix and **Ђ** (B x Γ) is derived by diagonalising the vector **β**.[195] The term 'net matrix' is used, as the diagonal elements in the matrix represent net outputs, as opposed to outputs of matrix **Ђ**. The net matrix is the same as Costanza *et al.*'s (1983) $\mathbf{U} - \mathbf{V}^T$ matrix.

Step 2 Calculation of the Ecological Multiplier

In order to calculate an ecological multiplier an exogenous vector, **Њ** (1 x Γ), of resource inputs (or residual outputs) measured in physical terms for each industry must be defined as,

$$\mathbf{\text{Њ}} = \text{э}(\mathbf{\text{Ћ}} - \mathbf{\text{Љ}}), \qquad (7.2)$$

where vector э (1 x B) denotes the embodied resource inputs (or residual outputs) required to produce B commodities. To solve for э, Equation 7.2 needs to be rearranged as:

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194 This Table is generated from the Auckland Region financial input-output table generated in Chapter 5 by applying the procedure outlined in Section 4.4.3.2.

195 In this formulation the number of commodities equals the number of industries (i.e. Γ = B). This approach facilitates matrix inversion, but assumes that only one homogeneous commodity output is produced per industry. Under ideal circumstances the matrices **U** and **V** of the economy-environment framework should be utilised – which permit multiple commodity outputs (or joint products) per industry. Since **U** and **V** are typically rectangular (i.e. B > Γ) the subsequent analysis would require the use of generalised or pseudo matrices. The major drawback of moving to multiple outputs per industry is that negative ecological multipliers may be generated. This is a long-standing problem in input-output analysis that is yet to be satisfactorily resolved.

$$\text{Њ} (\text{Ћ} - \text{Љ})^{-1} = \text{э} \qquad (7.3)$$

The solution vector э, the so-called ecological multiplier, represents the total (direct and indirect) embodied resource inputs (or residual outputs) measured in physical terms per unit of net output.

Step 3 Calculation of First Round Impacts

Greater insight into the distribution of ecological multiplier impacts may be gained by decomposition of the multiplier into first, second and subsequent round impacts. First round resource inputs (or residual outputs) requirements for every industry may be determined by diagonalising э, and in turn, postmultiplying by the inverse matrix $(\text{Ћ} - \text{Љ})^{-1}$ to obtain an 'evaluated' matrix, **Ж** (B x Г),

$$\text{Ж} = \hat{\text{э}} (\text{Ћ} - \text{Љ})^{-1}. \qquad (7.4)$$

The first round impacts for industry 1 are presented in the first column of the evaluated matrix, **Ж**. Similarly, the first round impacts for industry 2 are presented in the second column of the evaluated matrix, **Ж**, and so forth.

Step 4 Calculation of 2nd to nth Round Impacts

In this step the second round impacts for a given column industry of matrix **Ж** are generated.[196] To trace second round impacts we must first select the given column industry (industry 1 column in this example) from the evaluated matrix **Ж** for further analysis. The second round impacts resulting from the first round input of commodity 2 into industry 1, for example, may be computed as,

$$\text{ж}_1 \text{ъ}_{2,2,1} = \beta_{2,2,1} \qquad (7.5)$$

where ж_1 is a column vector (B x 1) of column industry 1 of the evaluated matrix **Ж**; $\beta_{2,2,1}$ is a vector (B x 1) of the second round impact (denoted by the first subscript), stemming from the first round input of commodity 2 (denoted by second subscript) into industry 1 (denoted by third subscript); and ъ is a scalar (1 x 1) ratio of commodity 2 input into industry 1 from the

[196] This column tells us the total embodied resource/residual requirements (a positive element) and the indirect embodied resource/residual requirements (negative elements). An additional row recording the direct resource/residual requirements (positive elements) may be augmented to matrix **Ж** to complete the analysis.

evaluated matrix Ж, divided by the 'net output of industry 2' from the evaluated matrix Ж. The same subscripting system is applied to $ъ_{2,2,1}$ as for $\boldsymbol{\beta}_{2,2,1}$.

The same procedure may be used to calculate the second round impacts of other commodity inputs in industry 1. In turn, the subsequent rounds of impact may be calculated in an analogous manner. Ultimately the so called 'infinite regress' situation arises, as the individual indirect contributions of elements in **β** become progressively smaller with subsequent rounds. The number of branches in the tree diagram increase exponentially with each subsequent round. The number of branches, ч, in any given round, ф, is given by,

$$ч = (\Gamma - 1)^{ф}. \tag{7.6}$$

The total number of branches across all rounds, $ф_j$, is given by,

$$\sum_{i=j}^{i=0} ч_j = \sum_{i=j}^{i=0} [(\Gamma - 1)^{ф}{}_j], \tag{7.7}$$

where i represents rounds 0 to j. The number of branches generated over a small number of rounds with a relatively small number of industries may be substantial. A complete lifecycle assessment of 48 industries over 5 rounds would, for example, generate 234,330,767 branches! Diagrammatic representation of the lifecycle assessment chains for even a single industry requires that selection criteria be applied to restrict the analysis to only the main embodied flows.

Step 5 Determination of the Direct and Total Multipliers Matrices

The direct multipliers matrix may be determined by dividing the physical amount of resource input (residual output), the elements in vector **Њ**, by the net output for each industry, the elements on the diagonal of matrix **Ћ**. Matrix **Я** is used to denote the result. These multipliers represent the resource input (residual output) in physical units per $ net output.

Total impact (direct plus indirect) may be measured relative to direct impact to produce an ecological multiplier analogous to the Type I economic multiplier used frequently in economic impact by economists. This matrix, **И**, may be derived by element-wise division of matrix Э by matrix **Я**.

In this Section, tree diagrams are used to illustrate the embodied appropriation of ecosystem services associated with producing a commodity.[197] Ecological multipliers, as calculated using the methodology presented in Section 7.2.1, may be used to create tree diagrams that show the conservative nature of embodied ecosystem service flows – *viz*, for a particular industry, ecosystem service inputs taken directly from the environment + ecosystem service inputs appropriated from the environment through economic production chains = the total ecosystem services embodied in any economic outputs produced by the industry. Moreover, for those ecosystem services appropriated through production chains it is possible to calculate the ecosystem service value appropriated at each point in the chain.

7.2.2 Direct Ecosystem Service Value by Industry

In Table 7.8, the direct value derived from Auckland Region's terrestrial ecosystems is disaggregated by 48 economic industries and households. In total this accounts for $1.03 billion, which represents 3.1 percent of the region's GRP ($33.2 billion). Compared with other regions (such as Canterbury $7.8 billion or 63 percent of GRP – refer to McDonald and Patterson (2003)) this represents a low level of appropriation. This result is however not surprising given: (1) the relatively small land area of the region (i.e. a larger land areas generally mean larger ecosystem service contributions); (2) the presence of a large urban land cover (i.e. the ecosystem services contribution by urban areas on a per hectare basis is substantially lower than other land cover types); and (3) the lack of consideration of ecosystem services embodied in goods and services purchased from other regions[198]. This contribution is likely to be very high given that Auckland Region is a significant appropriator of interregional and international land – refer to Chapter 8 for further details. Additionally, the ecosystem services provided by the Auckland Region marine ecosystem have been tentatively valued at $1.29 billion. A more detailed discussion of the contribution made by ecosystem services to the Auckland Region is given at the end of Appendix J by (1) ecosystem type, and (2) ecosystem service.

Households [49] rank highest in their appropriation of ecosystem services at $241.8 million (23.4 percent of the total). The primary industries of livestock and cropping farming [2]

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[197] Lifecycle assessment procedures have been formalised by the Society of Environmental Chemistry and Toxicology (1993). Four formal steps are recognised in lifecycle assessment: (1) goal and scope definition; (2) inventory analysis, to quantify the resource inputs and pollutant outputs at each step in the lifecycle; (3) impact assessment, to quantify the impacts, often using CO_2 equivalents, acidification equivalents or the like; and (4) interpretation of results and recommendations to reduce environmental impacts.

[198] The contribution made by the marine system is estimated to be $1.29 billion – refer to Appendix J for further details. Overall,

($200.6 million), mining and quarrying [8] ($134.8 million), dairy cattle farming [3] ($133.9 million), forestry and logging [6] ($49.0 million), other farming [4] ($46.2 million) and horticulture and fruit growing [1] ($20.5 million) rank in the top eight appropriators of ecosystem service value. Ranked third is the water supply industry [28] at $189.6 million with its heavy reliance on water supply services. In contrast, the lowest rankings tend to be for service industries such as finance [37], insurance [38], services to finance and investment [39] and real estate [40].

Table 7.8 Direct Value Derived from Auckland Region's Terrestrial Ecosystems, by Economic Industry, 1997-98

Industry	Direct Value	Direct Value (in rank order)
	$ million	
1 Horticulture and fruit growing	20.52	8
2 Livestock and cropping farming	200.55	2
3 Dairy cattle farming	133.85	5
4 Other farming	46.21	7
5 Services to agriculture, hunting and trapping	0.02	30
6 Forestry and logging	49.02	6
7 Fishing	0.02	32
8 Mining and quarrying	134.77	4
9 Oil and gas exploration and extraction	0.00	48
10 Meat and meat product manufacturing	0.02	29
11 Dairy product manufacturing	0.02	36
12 Other food manufacturing	0.05	20
13 Beverage, malt and tobacco manufacturing	0.01	38
14 Textile and apparel manufacturing	0.04	23
15 Wood product manufacturing	0.05	22
16 Paper and paper product manufacturing	0.02	28
17 Printing , publishing and recorded media	0.02	35
18 Petroleum and industrial chemical manufacturing	0.01	41
19 Rubber, plastic and other chemical product manufacturing	0.03	26
20 Non-metallic mineral product manufacturing	0.03	25
21 Basic metal manufacturing	0.02	33
22 Structural, sheet, and fabricated metal product manufacturing	0.02	34
23 Transport equipment manufacturing	0.01	39
24 Machinery and equipment manufacturing	0.02	31
25 Furniture and other manufacturing	0.02	37
26 Electricity generation and supply	0.01	42
27 Gas supply	0.00	47
28 Water supply	189.64	3
29 Construction	0.06	18
30 Wholesale trade	0.05	21
31 Retail trade	0.06	19
32 Accommodation, restaurants and bars	0.53	14
33 Road transport	0.15	17
34 Water and rail transport	0.01	40
35 Air transport, services to transport and storage	0.47	16
36 Communication services	0.03	24
37 Finance	0.00	44
38 Insurance	0.00	46
39 Services to finance and investment	0.00	45
40 Real estate	0.00	43
41 Ownership of owner-occupied dwellings	0.00	48
42 Business services	0.03	27
43 Central government administration, defence, public order and safety services	0.83	13
44 Local government administration services and civil defence	1.88	10
45 Education	1.21	11
46 Health and community services	0.49	15
47 Cultural and recreational services	10.20	9
48 Personal and other community services	1.16	12
49 Households	241.80	1
Total	1,033.96	

7.2.3 Direct and Indirect Ecosystem Services by Industry

Figure 7.9 and Figure 7.10 depicted the total appropriation of embodied ecosystem services by two key Auckland Region industries, namely, air transport, services to transport and storage [35] and business services [42].[199] These industries draw only very small amounts of ecosystem services directly from the environment, respective $472,500 (4.66 percent of their total embodied ecosystem service appropriation) and $30,200 (0.07 percent). By corollary, these industries must appropriate most of their ecosystem service requirements through their production chains. The air transport, services to transport and storage [35] industry, for example, appropriates ecosystem services indirectly to the value of $9.7 million (1.0 percent of total ecosystem service appropriation by Auckland Region industries[200]), while the business services [42] industry indirectly appropriates $41.0 million (4.1 percent).

Indirect appropriation through production chains of ecosystem services by the air transport, services to transport and storage [35] industry can be traced back primarily to direct appropriation from the environment by the cultural and recreation services [47] industry (> $3.0 million), water supply [28] industry (> $1.9 million) and the mining and quarrying [8] industry (> $0.9 million). This includes the indirect appropriation through production chains of primarily aesthetic, artistic, educational, spiritual and scientific values through the cultural and recreation services [47] industry, water through the water supply [28] industry, and raw materials through the mining and quarrying [8] industry. Lesser contributions are also made through the livestock and cropping [2] industry by way of erosion control, food production, waste treatment, raw materials and nutrient cycling services.

The indirect appropriation of ecosystem services through production chains by the business services [42] industry is by comparison dominated by aesthetic, artistic, educational, spiritual and scientific values obtained via the cultural and recreational services [47] industry ($25.1 million or 61.2 percent of the industry's total ecosystem service appropriation). Other significant embodied ecosystem services include water supply appropriated indirectly through the real estate [40] industry (> $3.2 million); paper products, climate regulation, and waste treatment through the forestry and logging [6] industry; and erosion control, food production, raw materials (fibre), and nutrient cycling services indirectly through the wholesale trade [30] industry.

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[199] This refers only to within region ecosystem service appropriation, i.e. it excludes the appropriation of ecosystem services embodied in imported goods and services.
[200] This does not include the ecosystem service appropriation by households.

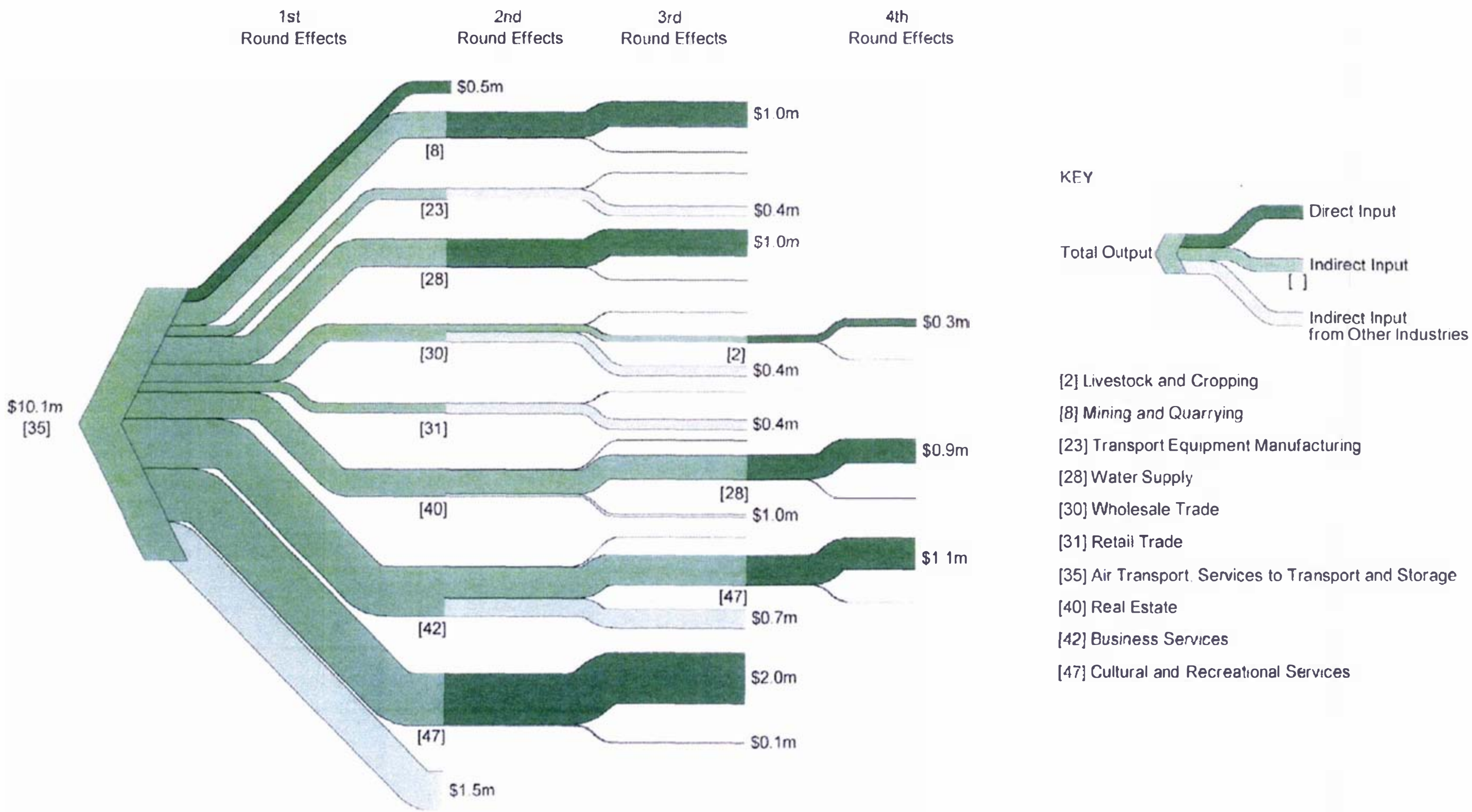

Figure 7.9 Total Embodied Ecosystem Services Appropriated by the Auckland Region Air Transport Industry, 1997-98

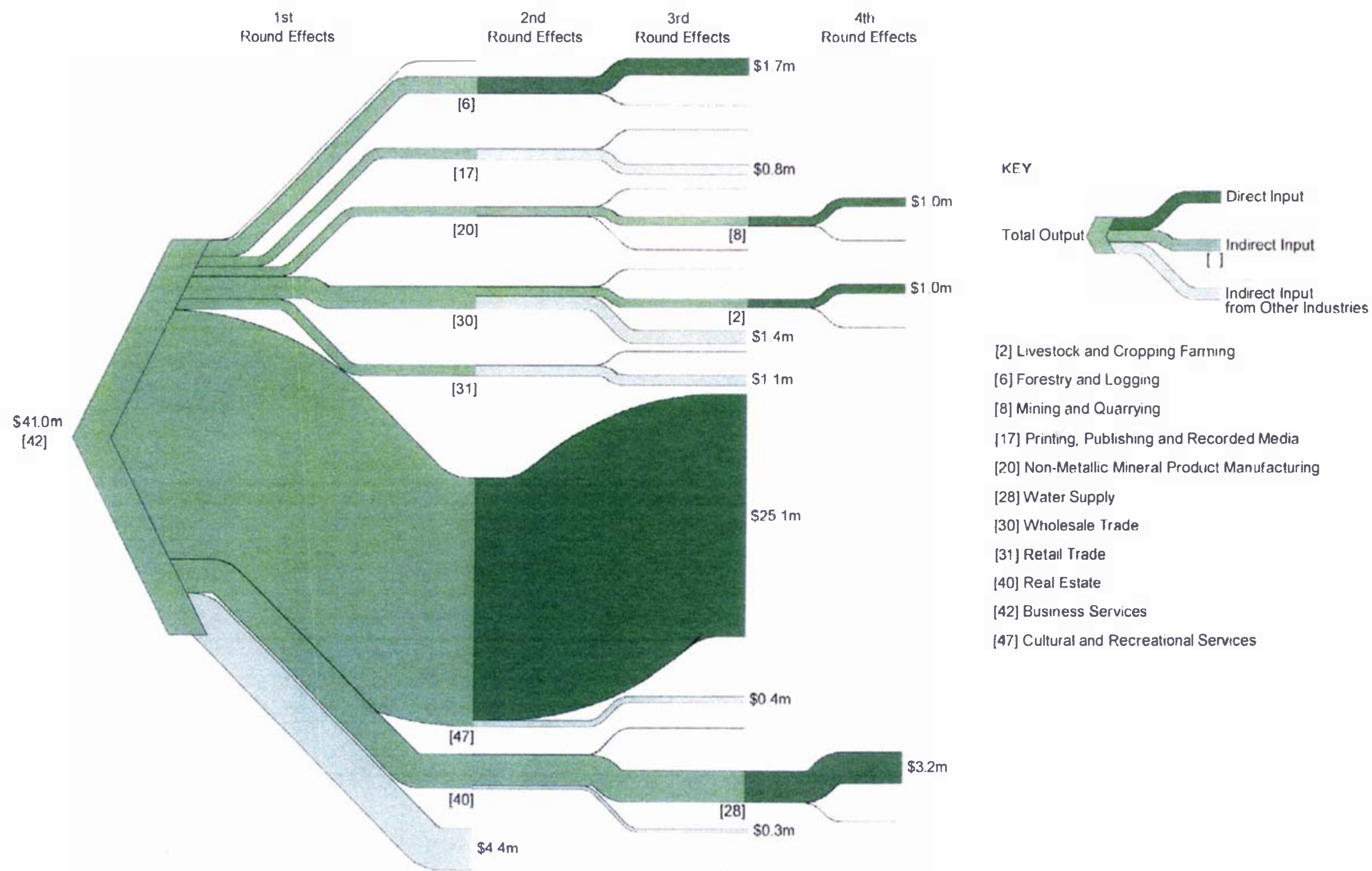

Figure 7.10 Total Embodied Ecosystem Services Appropriated by the Auckland Region Business Services Industry, 1997-98

Chapter Eight

Auckland Region's Ecological Footprint and Environmental Interdependencies with Other Regions[201]

This thesis has thus far focused on *structural analyses* of the interdependencies in and between the Auckland Region economic system and the Auckland Region environmental system (refer to Figure 4.9). In Chapter 8, through the use of the ecological footprinting method, the analysis is extended to quantify how the Auckland Region economic system depends on natural capital and ecosystem services drawn from other regions and countries.[202] This analysis is important as an urban region, like Auckland Region, is arguably more dependent on natural capital and ecosystem services obtained from other regions/countries than on those obtained within its own regional boundaries.

Specifically, this Chapter extends Bicknell *et al.*'s (1998) *input-output* based ecological footprinting method, to investigate the ecological interdependencies between Auckland Region and other regions[203] in New Zealand. This required the construction of 16 regional input-output matrices by regionalising the 1997-98 New Zealand input-output table using Jensen *et al.*'s (1979) GRIT (Generating Regional Input-Output Tables) methodology. From these regional input-output matrices, interregional flows of commodities were established using an optimisation model, which in turn enabled the ecological interdependencies to be tracked and quantified.

8.1 The Ecological Footprint Concept

8.1.1 What is the Ecological Footprint?

The Ecological Footprint is defined by Rees (2000, p.371) as the "area of productive land and water ecosystems require to produce the resources that a population consumes and assimilate the wastes that the population produces, wherever on Earth that land and water may be located".

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[201] A copy of most of this Chapter appears in the journal *Ecological Economics*, 2004, Volume 50, pp. 49-67. The introductory Section of this Chapter differs from that contained in the journal article, and the journal article contains a summary Section which does not appear in this Chapter.

[202] The ecological footprint uses embodied land as a proxy for the amount of natural capital consumed by a population or economy. As discussed in Section 8.2.2, there are other numeraires (apart from land) that can be used in this context.

[203] The method also quantifies how Auckland Region's ecological footprint is drawn from other countries. Due to lack of data, it is assumed that products imported from overseas have exactly the same embodied land per $ ratio as products made in New Zealand.

It can be seen as a sustainability indicator in two senses. Firstly, it measures the *ecological cost* (in land area) of supplying all of the goods and services to a human population. This recognises that people not only *directly* require land for agricultural production, roads, buildings and so forth, but that land is *indirectly* embodied in the goods and services that people consume. For example, the indirect (or embodied) land required to produce a kilogram of butter includes not only the land used directly in manufacturing, but *all* land embodied in the inputs that went into producing the butter – dairy farm land, land required to produce the packaging and so forth. In this sense, the footprint can be used to make visible the hidden ecological cost of an activity or population.

A second, and more controversial interpretation of the Ecological Footprint as a sustainability indicator, invokes the idea of *carrying capacity*. Carrying capacity in ecology is the maximum population a given land area can support indefinitely. The idea is relatively straightforward when applied to well-defined biological populations – e.g., a certain number of hectares are required to support a herd of deer. If the number of deer exceeds their carrying capacity then the population is said to be in 'overshoot'. Resources (mainly food) will become scarce and population die-back will occur. This idea is more controversial when applied to human populations, as in the *Limits to Growth* study, which projected a decline in global human population as it overshot its carrying capacity (Meadows *et al*., 1972; Meadows *et al*., 1992). Some proponents of footprinting argue that the total embodied land area required by a population should not overshoot its' biocapacity – e.g., Loh (2000) argues that the Ecological Footprint of the Netherlands at 92.9 million ha considerably overshoots its biocapacity of 37.4 million ha. Less dogmatically, it can be concluded that the Netherlands is in 'ecological deficit', in the sense that it is using more biologically productive land than is available within its borders.

8.1.2 History of the Ecological Footprint

The University of British Columbia's School of Community and Regional Planning developed the Ecological Footprint in the early 1990s. The concept was popularised by Wackernagel and Rees (1996) in the publication *Our Ecological Footprint - Reducing Human Impact on the Earth.* Wackernagel *et al.* (1999) acknowledge Vitousek's *et al.* (1986) study on the human appropriation of photosynthesis products as the intellectual predecessor to the footprint concept. However, its antecedents can be traced back a lot further.

In the eighteenth century the Physiocrats argued that the embodied land content of a commodity determined its value. For the Physiocrats, all value was derived from the land (nature), and in this sense agriculture was the only productive industry in the economy with the manufacturing and service industries considered sterile.

Classical economists, although not subscribing to an 'embodied land theory of value' did emphasise the idea of carrying capacity. Both Thomas Malthus (1766-1834) and David Ricardo (1772-1823) saw population being constrained by the carrying capacity imposed by land availability. Malthus argued that population growth wasn't sustainable in the long run, as it grew according to a geometric progression and it would eventually overshoot food supply from land that grew arithmetically. Ricardo didn't foresee an overshoot like Malthus did, but instead suggested that population growth would gradually approach its carrying capacity as food production was forced to use less fertile land.

In the modern era, Borgstrom (1967, 1973) developed the concept of 'ghost acreage' which is similar to the idea of the Ecological Footprint. This idea was further promoted by sociologist Catton (1982) in his book *Overshoot: The Ecological Basis of Revolutionary Change*. Ghost acreage is the additional land a nation needs in order to supply the net amount of food and fuel from sources outside the nation. The appropriation of ecosystem areas and services has also been a central theme in other approaches e.g., Folke *et al.* (1997) and Brown and Ulgiati (1998).

8.1.3 How is the Ecological Footprint Calculated?

Several methods have been advanced for calculation of Ecological Footprints – e.g., Wackernagel and Rees (1996), Folke *et al.* (1997), Bicknell *et al.* (1998), Wackernagel *et al.* (1999), Loh (2000), van Vuuren and Smeets (2000), and Ferng (2001). Although each of these methods has its own peculiarities and insights, many have their roots in the work of Wackernagel and Rees (1996).

Wackernagel and Rees Method

The Wackernagel and Rees calculation method begins with the construction of a 'consumption by land use' matrix for a given population. The consumption dimension covers food, housing, transport, consumer goods and services, while the land use dimension encompasses built-up areas (supporting roads, housing and other infrastructure), crop land and pasture (for production of food and other goods), managed forest (for production of wood products), and energy land (for sequestering carbon dioxide emissions resulting from the burning of fossil fuels).

Population data, together with consumption data (mainly in physical units), for each land use category are used to derive an average annual consumption per person (physical units per capita). Consumption is calculated by adding imports to domestic production and excluding exports. The land area utilised by each consumption category is then determined for each land use category. This requires dividing consumption in each land use category by a relevant global average yield to obtain land area. Global average yields are used so that comparisons can be made between the footprints of different nations and with the globe.

The land appropriated for energy consumption is treated separately, primarily due to the size of the contribution it makes. Wackernagel *et al.* (1999) distinguishes between five types of energy, namely: gas fossil, liquid fossil, solid fossil, firewood and hydropower. Nuclear power is treated as a fossil fuel. Energy land is calculated by assessing the amount of planted forest land required to absorb the CO_2 emissions released in the burning of fossil fuels. The role played by the oceans in CO_2 sequestration is also acknowledged. The oceans are assumed to absorb some 35 percent of CO_2 emissions at the global level. Once again, correction for trade is required as energy is utilised in the production of exported goods and services and conversely embodied in imports.

Aggregating the land area appropriated by each land use category generates the Ecological Footprint. Prior to aggregation each category is multiplied by an 'equivalence factor' to take account of differences in biological productivity. The Ecological Footprint may also be expressed in per capita terms, which permits the comparison between different nations, regions or populations.

Input-Output Method

The Ecological Footprint can also be calculated by using input-output analysis to track the flow of embodied land. This method of analysis which was first developed by Bicknell *et al.* (1998) and refined by Ferng (2001) and others, has not to date been widely used. It should, however, be noted that the calculation of embodied resources using input-output analysis has been widely undertaken since the early 1970's by analysts such as Hite and Laurent (1971), Herendeen (1972) and Wright (1975). The input-output method of calculating the Ecological Footprint attempts to situate the analysis in a rigorous mathematical framework, but draws upon many of the ideas and principles of the Wackernagel and Rees method. Readers should refer to Section 8.3.6 of this Chapter for a discussion of the limitations of input-output analysis in ecological footprinting.

8.2 Critique of the Ecological Footprint Concept

Costanza (2000) and Moffatt (2000) argue that the key feature of the Ecological Footprint is that it provides an effective heuristic and pedagogic tool that captures current human resource use in an easily digestible form. In this way, footprinting frequently promotes discussion on issues directly relevant to sustainable development – viz., issues such as: (1) the finite dimensions of human activity; (2) the key resources and ecosystem functions for sustainable development; (3) the role played by trade in distributing ecological resources and pressures; (4) the selection of indicators for monitoring progress toward sustainable development and so forth. The Ecological Footprint methodology does, however, have a number of well-known weaknesses and limitations that are described below.

8.2.1 Lack of Common Definitions and Methodologies

There is no accepted methodology for calculating the Ecological Footprint. The Ecological Footprint is not, for example, constructed according to widely accepted international conventions such as that used in the United Nations System of National Accounts (UNSNA). This has led to ambiguities in interpreting the results of various Ecological Footprint studies. For instance, estimates of New Zealand's Ecological Footprint range between 3.49 and 9.6 ha per capita (Bicknell *et al.*, 1998; Wackernagel *et al.*, 1999; Loh, 2000). Investigation of these studies reveals that differences result largely from the assumptions made concerning biological productivity, the use of equivalence factors, and the calculation of energy land. To avoid misinterpretation in this Chapter, and to allow comparison with earlier footprint estimates, differences in assumptions between three different calculation methods are outlined in Table 8.1.

Table 8.1 Assumptions Made by Three Different Ecological Footprint Calculation Methods

Bicknell *et al*. (1998)	Loh (2000)	This paper
Applies local yields for pasture, arable and forest land	Applies global average yields for pasture, arable and forest land[a]	Applies local yields for pasture, arable and forest land
Does not apply equivalence factors	Applies equivalence factors when aggregating land types[a]	Does not apply equivalence factors
Applies an international energy-to-land ratio obtained from Wackernagel and Rees (1996)	Applies a world average CO_2 absorption factor[b]	Applies a CO_2 absorption factor for New Zealand *Pinus radiata*[c]
Ignores CO_2 absorption by oceans	Assumes oceans absorb 35 percent of CO_2 emissions	Ignores CO_2 absorption by oceans
Excludes sea space	Includes sea space, estimated to be 0.1 ha per capita for NZ	Excludes sea space
Considers ecological interdependencies between regions as an aggregate (total imports)	Considers ecological interdependencies between regions as an aggregate (total imports)	Makes explicit ecological interdependencies between regions[d]
Based on input-output analysis	Based on work of Wackernagel and Rees (1996)	Based on input-output analysis

Notes:
a Discussed further in Section 8.2.4
b Discussed further in Section 8.2.3
c Discussed further in Section 8.2.2
d Discussed further in Sections 8.2.5 and 8.3

8.2.2 Why Use Land as the Numeraire?

Why should 'embodied land' be used as the numeraire for a sustainability indicator? Others have argued (Slesser, 1973; Gilliland, 1975; Costanza, 1980; H.T. Odum, 1983; Herendeen, 1998) that 'embodied energy' or 'embodied solar energy' is a more appropriate numeraire. Land isn't the only scarce natural resource, so why should it be the only resource entered into the calculation of a sustainability indicator? Arguments alluding to the non-substitutability of land are not compelling, as it could be argued that other natural resources also don't have substitutes – e.g., solar energy. By using input-output analysis to calculate footprints, as is applied in this thesis, the ecological consequences of human activity on other key resources are easily determined. Energy Analysis, for example, has been widely applied in estimating energy embodied in human activities[204]. The focus of this Chapter is however on the appropriation of biologically productive land.

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[204] Examples include Gilliland (1975), Hannon (1979), Costanza (1980), and Giampietro and Pimentel (1991).

8.2.3 Why Include Hypothetical Energy Land?

The hypothetical land required to absorb atmospheric CO_2 emissions resulting from the burning of fossil fuels, often constitutes more than 50 percent of the Ecological Footprint. Critics such as Ayres (2000) find this result questionable. According to them, it assumes that afforestation is the preferred option for CO_2 sequestering. However, the use of renewable energy sources such as wind power and energy efficiency initiatives are realistic alternatives (apart from afforestation) for reducing CO_2 emissions. Alternatives such as liquefying CO_2 and pumping it into the ocean depths or into oil and gas fields replacing the fuel extracted also exist. Planting production forest to sequester CO_2 is arguably only a temporary measure. The forests will die, be harvested as products that will eventually decompose, or be used as a fuel source, all of which will result in CO_2 being re-released back into the atmosphere.

Another critical issue with the Ecological Footprint is that it exclusively focuses on energy related CO_2 emissions, neglecting the ecological consequences caused by other emissions – e.g., the depletion of ozone by CFCs, or acidification caused by SO_2 and NO_x. More importantly, the Ecological Footprint as currently formulated overlooks pollution and wastes generated by other unsustainable practices, such as the disposal of non-biodegradable consumer wastes (e.g., plastics, metals) and persistent toxins (e.g., rubbish leachate). These issues are not addressed in this Chapter of the thesis, although it is recognised that they are important issues that need to be addressed in the further development of the footprint indicator.

8.2.4 Is All Land the Same?

The use of equivalence factors during the aggregation of Ecological Footprint components (built-up land, arable land, forest land *etc.*) is contentious. These equivalence factors recognise that adjustments need to be made to land areas (ha) to take into account variations in biological productivities. For example, fertile flood plains may have a biological productivity several times that of mountainous land, and adjustments need to be made to reflect this difference. It can be argued that this narrow focus on biological productivity ignores other factors that determine the relative value of different types of land – e.g., cultural values, social preferences or relative scarcity.

International comparison of Ecological Footprints requires consideration of differences in biological productivity. Such differences are primarily due to environmental factors – i.e., solar flux, soil type, climatic conditions and type of vegetation cover. This issue is addressed in Ecological Footprint calculations by relating consumption to global average yields rather than local yields[205]. Such an approach is problematical as it produces results that are not comparable with the actual land area occupied by the appropriating population. At a national or sub-national level, it is often desirable to be able to examine ecological consequences in terms of actual occupied land area – a unit of measurement familiar to the resident communities.

In this Chapter of the thesis, neither global average yields nor equivalence factors are used, except when international comparisons are made in Section 8.4.7.

8.2.5 What Spatial Boundaries?

The selection of appropriate spatial boundaries is a critical issue in footprinting. For example, footprints can be calculated at global, national, regional and local (city) scales. Wackernagel and Silverstein (2000) argue for political or cultural boundaries, as they represent the level at which environmental policy and decision-making is most often made. By contrast, van den Bergh and Verbruggen (1999) dispute the use of such boundaries on the grounds that they have no environmental meaning, favouring instead hydrological, climate zone, or larger connected ecosystem boundaries. In this Chapter, New Zealand Regional Council areas are used which reflect both political and environmental boundaries.

Closely associated with the selection of appropriate spatial boundaries are the ecological implications of trade. Rees (1992) argues that trade has the effect of physically and psychologically distancing populations from the ecosystems that sustain them. From a regional perspective, information is required not only on footprint size (and on its component shares – e.g., agricultural, arable, forest, built-up and energy land), but also on the origins of contributions made by each imported component and how sustainable it is. For this reason the Ecological Footprint methodology is extended in this Chapter of the thesis to include an analysis of the ecological interdependencies of New Zealand regions, in order to consider not only the footprint from the consumption (end-use) perspective, but also the production (source) perspective.

8.2.6 Dynamics – What About the Future?

The Ecological Footprint provides a snapshot of a population's environmental requirements using current technology under prevailing management practices and social values. Even if the

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[205] Global (Loh, 2000) average milk yields may differ substantially from local yields. In New Zealand, for example, the local yield for milk production is 1,759 kg ha^{-1}, which compares with a global average yield of 336 kg ha^{-1}. Therefore, applying a global average milk production yield results in a domestic Ecological Footprint contribution that is 5.24 times the actual land area used for milk production.

footprint for a particular population is calculated at regular intervals, the results are always out of date – in this respect the footprinting only tells us 'yesterday's news'. Key dynamic components of the sustainability equation such as intergenerational equity, technological change, and the adaptability of social systems are simply overlooked. Moreover, nature is characterised by complex adaptive systems with non-linearities, feedback loops, and thresholds (Holling, 1973; Levin, 1998). By ignoring such dynamics the Ecological Footprint cannot inform us on the ecological consequences of likely futures, or even possible scenarios. This Chapter makes no attempt to address these issues.

8.2.7 Policy Relevance – A Policy Evaluation Tool?

Proponents of the Ecological Footprint (e.g., Wackernagel and Rees (1996), Wackernagel and Silverstein (2000)) advocate that the footprint can evaluate potential strategies for avoiding ecological overshoot. The Ecological Footprint is seen as an instrument that provides decision-makers with "a physical criterion for ranking policy, project or technological options accounting for their ecological impacts" (Wackernagel and Rees, 1996, p.27). This claim has, however, been hotly contested. Ayres (2000) asserts that footprinting provides no meaningful rank ordering, and even less so any value for policy evaluation. This view is shared by Moffatt (2000, p.360) who notes "it offers no policy suggestions apart from either including more land, reducing population, or reducing consumption per head".

Although it is agreed that the policy instruments or actions required to counteract overshoot cannot be implied from the Ecological Footprint method, it is argued here that the footprinting does provide a broad level measurement of ecological impact. In this way, the Ecological Footprint may be used to signal the relative ecological cost of different policy options. Careful consideration of the components of the footprint may also help to evaluate the relative ecological cost of various human activities, enabling policy analysts to identify 'hotspots' for policy action. By far the greatest contribution that footprinting can make to policy and decision-making is as an educative tool to stimulate thinking about the far-reaching nature of the indirect ecological effects of human activities.

8.3 An Input-Output Method for Estimating Auckland Region's Ecological Footprint

Much of the Ecological Footprint work undertaken to date is based on methodology that lacks formal structure. Some approaches may even be considered to be *ad hoc*. A major limitation of such methods is that they may lead to results that are not easily reproduced, either through time or across space. In turn, this restricts comparability or leads to inconsistencies that are more an artefact of the method rather than actual differences. Such concerns led Bicknell *et al.* (1998) to develop an alternative formulation of the Ecological Footprint based on input-output analysis.

8.3.1 Accounting Identity of the Component Parts of the Regional Ecological Footprint

In this Chapter of the thesis, Bicknell *et al.*'s (1998) input-output approach is extended to formally permit calculation of regional ecological footprints and to make explicit interregional appropriation of land. Essentially, the regional ecological footprint is defined by the following accounting identity:

$$\mathbf{EF} \equiv \alpha + (\beta_1 + \beta_2 + \ldots + \beta_{n-1}) + \delta \qquad (8.1)$$

where: α = land appropriated from within the study region; $\beta_1 + \beta_2 + \ldots + \beta_{n-1}$ = land appropriated from other regions (1 ... n-1); and δ = land appropriated from other countries.

Fully worked examples of how to calculate each of the three components of regional ecological footprints is outlined in a recently published report by McDonald and Patterson (2003b). In Section 8.3.4 of this Chapter, we only outline how to calculate the *land appropriated from other regions* component ($\beta_1 + \beta_2 + \ldots + \beta_{n-1}$), and we refer readers to Bicknell *et al.* (1998) on how to calculate both the land appropriated from within the study region (α) and the *land appropriated from other countries* (δ).

8.3.2 Generation of Input-Output Tables

Regional input-output matrices need to be calculated for the study region and the other regions in the nation. These regional input-output matrices and the data contained in them are then subsequently used in the calculation of each of the *main components* in the regional ecological footprint identity (refer to Equation 8.1).

In this Chapter of the thesis, these matrices were derived using the GRIT method, which was developed by Jensen *et al.* (1979) and West *et al.* (1980)[206]. This method consists of a series of mechanical steps that reduce national input-output coefficients to sub-national (regional) equivalents, while providing opportunities for the insertion of superior data. Such non-survey based methods of generating regional input-output matrices are frequently utilised, as in this

[206] Studies that have applied the GRIT method in New Zealand include Butcher (1985), Kerr *et al.* (1986) and the Ministry of Agriculture (1997).

thesis, when time, cost and data constraints preclude generation of matrices based on survey data.

8.3.3 Calculation of the Land Appropriated Within the Study Region (α)

The land appropriated from industries within the study region is calculated using the Bicknell *et al.* (1998) method. Readers should refer to that paper for full details. Instead of using a national input-output matrix (as did Bicknell *et al.*, 1998), we used a regional input-output matrix.

8.3.4 Calculation of the Land Appropriated from Other Regions ($\beta_1 + \beta_2 + \ldots + \beta_{n-1}$)

The following five-step process calculates the land appropriated by the study region from other regions:

Step 1 Determination of the Regional Imports ($) Matrix, $\mathbf{G}_r$, for Region 1

Each industry in the study region purchases commodities ($) from various regions in the nation. For a given industry in New Zealand, as in most countries, it is not known exactly from which region these commodities originate. This is estimated in this thesis by solving an optimisation problem. It is assumed that each industry within a region will seek to source commodities from supplier regions closest to them in terms of travel time. Thus, minimisation of travel time is to set the objective function, while known levels of industry imports (and exports) are used as the binding constraints[207]. Fuller details of this optimisation problem are contained in Appendix C.

Solving the optimisation problem enables matrices $\mathbf{G}_r$ to be defined for each region that exports commodities to the study region – in our study there are 15 non-study regions. Matrices $\mathbf{G}_r$ define the exact quantities of commodities being imported into each study region industry from each of the non-study regions.

[207] This assumes that transport operators will only minimise their travel times, whereas in actuality other factors may also come into play. Nevertheless, analytical tests for the results reported in Section 8.4 show that the optimisation problem is relatively constrained with a small feasibility space i.e., differences between optimal and actual flows will be minimal.

Step 2 Determination of the Land (ha) Embodied in Regional Imports, $\boldsymbol{K_r}$, for Region 1

The imports matrix $\mathbf{G_r}$ (from Step One) quantifies the imports of commodities into a given industry (in the study region) from industries in Region 1. These quantities of commodities are enumerated in monetary ($) terms. They are converted to embodied land terms (ha) by:

$$\mathbf{K_r} = \mathbf{H_r}\,\mathbf{G_r} \tag{8.2}$$

where: $\mathbf{K_r}$ = embodied land matrix $[i \times (j+f)]$, describing the land embodied in imports into industries j and into final demand f derived from industries i in Region 1; $\mathbf{G_r}$ = imports matrix $[i \times (j+f)]$, describing the $ imports from industries i from Region 1 into industry j and into final demand f; and $\mathbf{H_r}$ = inverse Leontief matrix $(i+j)$, describing the direct plus indirect land requirements from industries i needed to generate an additional unit of output ($) in industry j in Region 1.

Step 3 Determination of the Land Supporting Domestic Consumption, $\boldsymbol{M_r}$, ha, for Region 1

In the footprint analysis we are only concerned with the Land required to support domestic consumption – not the portion of land that passes out of the study region as land embodied in exports. This is calculated by:

$$\mathbf{M_r} = \mathbf{K_r}\,\hat{\mathbf{L}}_r \tag{8.3}$$

where: $\hat{\mathbf{L}}_r$ = final demand matrix $[(j+f) + (j+f)]$, describing on the diagonal the fraction of final demand consumed in the study region; and $\mathbf{M_r}$ = domestic land consumption matrix $[i \times (j+f)]$, describing the land embodied in industry j output and final demand f which supports domestic consumption in the study region. The data for $\hat{\mathbf{L}}_r$ is calculated from the study region's input-output matrix generated by the GRIT process referred to in Section 8.3.2.

Step 4 Repeat Steps One to Three for the Calculation of Energy Land, Region 1

Energy land represents the area of planted forest needed to sequester CO_2 emissions resulting from the burning of fossil fuels.

The approach used to calculate the energy land appropriated from Region 1 is analogous to that used to calculate the land appropriated from Region 1. This means steps one to three are now repeated with the exception that matrix $\mathbf{H}_r$ is replaced with an inverse Leontief matrix for energy land.

Step 5 Repeat Steps One to Four for all Regions

Steps One to Four described the process of calculating the land and energy land appropriated from other regions. This needs to be repeated for all other regions in the nation – in our study this included 15 other regions.

Once the calculations have been repeated for all other regions, the data then needs to be compiled into one matrix **T**. Matrix **T** represents the total land appropriated by each industry (column) according the industry-region combinations (rows). An illustrative example of matrix **T** is provided by Table 8.2. Each of the components of the Equation 8.1 expression $\beta_1 + \beta_2 + \ldots + \beta_{n-1}$ (land appropriated from other regions) can now be directly abstracted from the Matrix **T**. For example, β_1 is the grand total for Region 1 (in Table 8.2) – it is the sum of the column totals (or row totals) which is 2,701 hectares. By summing these grand totals for each of the non-study regions $\beta_1 + \beta_2 + \ldots + \beta_{n-1}$, the overall land appropriated from all other regions is determined.

Table 8.2 Illustrative Example of the Matrix T: Land Appropriated From Other Regions $\beta_1 + \beta_2 + \ldots + \beta_{n-1}$

Imports from Sectors in Other Regions	Study Region Sectors and Final Demand				
	Agriculture	Manufacturing	Services	Final demand	Total
Region 1					
Agriculture	14	653	607	1,079	2,353
Manufacturing	0	4	5	8	17
Services	1	13	81	237	332
Sub-total	15	670	693	1,324	2,702
Region 2					
Agriculture	75	2,007	1,053	2,094	5,229
Manufacturing	0	2	2	5	9
Services	4	30	230	693	957
Sub-total	79	2,039	1,285	2,792	6,195
Region 3					
Agriculture	591	14,465	1,875	1,042	17,973
Manufacturing	0	4	3	3	10
Services	1	31	8	7	47
Sub-total	592	14,500	1,886	1,052	18,030
Total	686	17,209	3,864	5,168	26,927

Notes:
1. All values are in ha per year unless otherwise stated.
2. Reading the Table: The land embodied in interregional imports into the study region industries and final demand are obtained by reading down the column e.g., the land embodied in agricultural sector imports (from Region 1) into the study region's manufacturing sector is 607 ha, and so forth for the other interregional imports reading down the column.
3. The values (not including sub-totals and totals) for Region 1 are the elements in the matrix that results from adding the matrices Mr (for land) and Mr (for energy land) for that region. The same arithmetic applies for the values for Regions 2 and 3.
4. $\beta 1$ = 2,702 ha (total for Region 1), $\beta 2$ = 6,195 ha (total for Region 2), $\beta 3$ = 18,030 ha (total for Region 3). The sum of $\beta 1 + \beta 2 + \beta 3$, which is 26,927 ha in this example, is the total land appropriated from other regions.

8.3.5 Calculation of Land Appropriated from Other Countries (δ)

The land appropriated from other countries is calculated using the Bicknell *et al.* (1998) method. Readers should refer to that paper for full details. Essentially, the Bicknell *et al.* (1998) method assumes that products imported from overseas have exactly the same embodied land per $ ratio as products made in New Zealand. This assumption is necessary due to the lack of such data for overseas countries, although superior data can be substituted if it is available.

8.3.6 Limitations of Using Input-Output Analysis

There are a number of critical assumptions that underpin the method presented in this Chapter which stem directly from using input-output analysis. Rather than recite these assumptions of input-output analysis, which are well documented elsewhere (e.g., Richardson (1972)), we instead focus on those assumptions we consider most relevant in applying input-output analysis to footprinting. We also refer readers to Bicknell *et al.* (1998) for a more detailed discussion of the limitations of applying input-output analysis to ecological footprinting.

In Leontief-based input-output analysis, as described in this Chapter, the homogeneity assumptions require that only one commodity be produced per industry. This does not always occur in reality as industries are often involved in 'joint production' – e.g., a dairy farm may use land to produce not only milk-fat but also lesser amounts of beef or horticultural product. There are, however, input-output methods (e.g., Costanza and Hannon, 1989) that can be applied to deal with this joint production problem, which could be adapted for use in ecological footprinting.

The inter-industry linkages in an economy generally represent flows of physical goods. In input-output analysis such flows are usually summarised in a transactions table denominated in monetary units. However, the use of monetised tables can lead to problems if the price per tonne paid for a given product differs across purchasing industries. If industry 1, for example, purchases 10 kg of goods at 0.20 $\$kg^{-1}$ and industry 2 purchases 10 kg of goods at 0.10 $\$kg^{-1}$ from the same industry, then both industries receive the same physical quantity of goods (10kg), but spend different amounts of $2.00 and $1.00 respectively. This implies, from a monetary transaction perspective, that the land embodied in industry 1 purchases is twice that of industry 2 purchases – whereas, from a physical perspective, both industries are purchasing the same physical quantity of goods. This effect may result in both under-and-overestimation of industry contributions made to the Ecological Footprint.

The input-output method as presented in this Chapter makes two particular assumptions concerning imported commodities. Firstly, it assumes that imported commodities are essentially final or finished goods. This implies that only backward linkages through the economy in the region of origin are measured. If, however, there are imported commodities requiring further processing in the study region, then forward linkages may also need to be estimated. Secondly, the method assumes that imported commodities have the same embodied land-to-output ($) ratio as in the domestic economy – this is probably a reasonable assumption in most cases. Ideally, the actual land-to-output ($) ratios for imported commodities should be used in the analysis, but unfortunately such data is rarely available thereby necessitating the use of these surrogate values.

8.4 Ecological Footprint of the Auckland Region

The methodology described in Section 8.3 was used to calculate Auckland Region's Ecological Footprint and to identify its source-of-origin. All calculations are in terms of *actual* biological productive land areas needed to satisfy domestic final demand, based on local yields. Similarly, no adjustments are made for differences in biological productivity between land types when aggregating – i.e., no equivalence factors are applied. The results presented here are aggregated to facilitate comparison with earlier studies by Bicknell *et al.* (1998) and McDonald and Patterson (2003b).

8.4.1 Brief Description of the Auckland Region

The Auckland Region is New Zealand's largest and fastest growing region, with a population of 1,159,400 in 1998 (Statistics New Zealand, 1998h). Nearly 30 percent of New Zealanders live in the Auckland Region. Most of the region's residents live in the Auckland metropolitan area. The metropolitan area itself is a sprawling city of largely detached single storey dwellings.

Geographically the Auckland metropolitan area is located on an isthmus between two natural harbours. From north to south the region measures 120 kilometres and at its widest point is 60 kilometres. The land area of the region is 560,000 ha (2 percent of New Zealand's land area).

Auckland Region is New Zealand's commercial hub having the highest proportion of people employed in finance, insurance, property, wholesale trade and business service industries (Statistics New Zealand, 1998b). The traditional economic base of Auckland Region has been manufacturing, but this has experienced some decline in recent years due to impacts of trade liberalization and globalisation.

8.4.2 Data Sources

Input-output tables for New Zealand's 16 Regional Council areas are derived from the national inter-industry table produced by Statistics New Zealand using the GRIT method (1991, 1998i, 1998f, 1999c). Each input-output matrix covers 23 industries. Estimates of land use data by economic industry are based on data gathered from Quotable Value New Zealand (1998), Statistics New Zealand (1998h, 1998a), Ministry of Agriculture and Forestry (1999), and Works Consultancy Services Ltd (1996). These estimates exclude national parks, lakes, rivers and the marine environment. Energy related CO_2 emissions by economic industry were obtained from the Energy Efficiency Conservation Authority (1997). The conversion of CO_2 emissions into energy land is based on sequestration data obtained from Hollinger *et al.* (1993). They estimate that an average hectare of *Pinus radiata* in New Zealand absorbs 3.6 t of C, which equates to 0.0758 ha per t of CO_2[208]. Appendix K describes the methodological processes used in calculating the environmental flows of land and energy into the Auckland Region – a more detailed analysis these flows is also given. Population statistics are based on sub-national estimates produced by Statistics New Zealand (1998k).

8.4.3 Auckland Region's Ecological Footprint Disaggregated by Land Type

Agricultural land consists of land used for sheep and beef, dairy, mixed livestock, other farming and horticulture. Auckland Region appropriates 1,525,000 ha of agricultural land for domestic use or 1.32 ha per capita (Table 8.3). Over half of this land, 805,000 ha, is embodied in agricultural products imported from other New Zealand regions. Only 168,000 ha or 11.0 percent of agricultural land was appropriated from within the region, particularly from livestock farms in the south of the region. Significant amounts of land are also planted in horticultural crops such as onions, spinach, capsicum and Asian vegetables, with lesser amounts in strawberries and persimmons.

Table 8.3 Auckland Region Ecological Footprint Disaggregated by Land Type, 1997-98

Land type	Within region land	Land from other NZ regions	Land from other nations	Land type total	ha per capita	% of land type total
Agricultural land	168,000	805,000	552,000	1,525,000	1.32	65.7
Forest land	6,000	45,000	50,000	101,000	0.09	4.4
Built-up land	96,000	17,000	32,000	144,000	0.12	6.2
Energy land	355,000	18,000	177,000	550,000	0.47	23.7
Total	624,000	885,000	810,000	2,320,000	2.00	100.0

Note: All values are in ha per year unless otherwise stated. Figures may not add up to the stated totals due to rounding.

Forest land refers to forest plantings used for commercial gain. It does not include the hypothetical forest planted to sequester CO_2 emissions. Some 94.5 percent of forest land appropriated by domestic final demand is imported into the region. Only 6,000 ha is appropriated from within the region, made up almost entirely of *Pinus radiata.* On a per capita basis forest land appropriation amounts to 0.09 ha or 4.4 percent of the region's footprint.

[208] It is worth noting that these figures may vary considerably between regions depending on plantation age, soil type, climatic conditions and so on. The possibility of planting indigenous forest to sequester CO_2 emissions is also ignored (refer to Hall and Hollinger (1997) for further debate concerning this issue).

Built-up land represents built-up areas that host human settlements. This includes land used for housing, commercial and governmental purposes[209]. It accounts for 6.2 percent of the region's footprint and equates to 0.12 ha per capita. Some 96,000 ha or 66.4 percent is appropriated from within the region, including 38,000 ha for housing. It also captures the region's road network, which exceeds 7,500km or 8 percent of total national road length (Works Consultancy Services, 1996).

Energy land is a measure of the hypothetical planted forest needed to sequester CO_2 emissions. It accounts for 550,000 ha or 23.7 percent of the region's footprint. This is relatively low when compared to most developed nations. Loh (2000), for example, estimates Canada's energy land contribution to be 47.0 percent, Australia's to be 56.4 percent and the United States' at 60.8 percent. Auckland Region's relatively low energy land component can be explained by: (1) the *Pinus radiata* CO_2 sequestration factor – which is significantly higher than the global average used by Loh (2000), (2) the structure of the Auckland regional economy, which is dominated by less energy intensive light manufacturing and service sectors, rather than more energy intensive heavy manufacturing sectors, (3) the low electricity CO_2 emission rate – a result of the high proportion of electricity (64.5 percent) drawn from hydro sources.

8.4.4 Auckland Region's Ecological Footprint Disaggregated by Economic Industry

The appropriation of land embodied in goods and services purchased by the region's primary sectors (agriculture, forestry, fishing and hunting, and mining and quarrying) accounts for 168,000 ha which represents 7.2 percent of the region's footprint (Table 8.4). The agriculture sector appropriates most of this land in the form of internal transactions e.g., sales and purchases of stock from within the agriculture sector.

[209] Large commercial and governmental land users include office and retail space, warehouses, amusement parks, holiday parks, car parks, schools, hospitals, prisons and military bases.

Table 8.4 Auckland Region Ecological Footprint Disaggregated by Economic Industry, 1997-98

Economic sector	Within region land	Land from other NZ regions	Land from other nations	Economic sector total	ha per capita	% of economic sector total
Agriculture	105,000	37,000	5,000	147,000	0.13	6.3
Forestry	2,000	18,000	0	20,000	0.02	0.8
Fishing and hunting	0	0	0	0	0.00	0.0
Mining and quarrying	0	0	0	1,000	0.00	0.0
Manufacturing	109,000	794,000	224,000	1,127,000	0.97	48.6
Utilities and construction	44,000	16,000	35,000	96,000	0.08	4.1
Services	195,000	7,000	166,000	369,000	0.32	15.9
Domestic final demand	169,000	13,000	379,000	562,000	0.48	24.2
Total	624,000	885,000	810,000	2,320,000	2.00	100.0

Note:
All values are in ha per year unless otherwise stated. Figures may not add up to the stated totals due to rounding.

On a sectoral basis, the largest appropriation of land is by the manufacturing sector (1,127,000 ha), accounting for 48.6 percent of the region's footprint. Of this amount, 794,000 ha are embodied in imports from other New Zealand regions. These imports largely represent backward linkage purchases of land embodied in agricultural products. This is not surprising given that the region's agriculture sector is unable to satisfy local demand[210]. Of the 109,000 ha appropriated locally by the manufacturing sector, most is used in the manufacture of food and beverages, with lesser amounts in the production of textiles and clothing.

Auckland Region's service sector appropriates 369,000 ha or 15.9 percent of the region's footprint. Interestingly, this is almost 8.0 times greater than the actual land area occupied by the service sector. This is because service industries are typically at the end of the value-added chain and therefore they tend to have significant backward linkages, many of which appropriate land.

Domestic final demand, although not strictly an industry, is included in Table 8.4 for completeness. This category encompasses land occupied by housing, land embodied in goods and services purchased by households, and smaller amounts of land embodied in non-marketable governmental goods and services consumed by the region's communities. Households appropriate 562,000 ha of biologically productive land, which is almost one quarter of the region's footprint. Most of this land is embodied in consumer goods purchased from

[210] The respective employment location quotients for agriculture and forestry relative to the national are estimated to be 0.24 and 0.28.

other nations. This includes goods that are imported directly by wholesalers and retailers and then resold to households without further processing.

8.4.5 Auckland Region's Ecological Balance of Trade

An input-output formulation of the Ecological Footprint permits an 'ecological balance of trade' to be calculated on a systematic basis. Auckland Region's ecological balance of trade by land type is depicted in Table 8.5. This Table indicates that 2,509,000 ha of land were appropriated from outside the region (this includes the 1,696,000 ha supporting domestic consumption), while 1,089,000 ha were embodied in exported goods and services. Thus, the Auckland Region is a significant net importer (1,420,000 ha) of biologically productive land.

Table 8.5 Ecological Balance of Trade for the Auckland Region Disaggregated by Land Type, 1997-98

Land type	Land embodied in imports	Land embodied in exports	Balance of trade
Interregional trade			
Agricultural land	1,293,000	14,000	-1,278,000
Forest land	124,000	5,000	-118,000
Built-up land	19,000	1,000	-18,000
Energy land	28,000	9,000	-20,000
Interregional balance of trade	1,464,000	29,000	-1,434,000
International trade			
Agricultural land	711,000	721,000	10,000
Forest land	63,000	94,000	32,000
Built-up land	59,000	21,000	-38,000
Energy land	213,000	224,000	11,000
International balance of trade	1,046,000	1,060,000	14,000
Balance of trade	2,509,000	1,089,000	-1,420,000

Note:
All values are in ha per year. Figures may not add up to the stated totals due to rounding.

As previously noted, it is not only important to evaluate solely the *total quantity* of land appropriated from outside the region, but also to consider where this land originates. At its source-of-origin, the land may be farmed unsustainably (e.g., overcropping or accelerated erosion caused by sub-standard farming practices) or it could be used sustainably (e.g., by using nutrient recycling or minimising fossil fuel inputs). Or perhaps the land could be drawn from a source nation where land is scarce and there is much poverty. In terms of sustainability (and equity) arguments, these factors relating to the source-of-origin of land could be more important than just considering the total quantity of appropriated land – viz, it is not just the size of the footprint that counts, but also *where* and *how* the footprint falls, and *what* impact it has on the environment.

Figure 8.1 graphically depicts the origin of biologically productive land imported into Auckland Region. Approximately 15.5 percent (227,000 ha) of the land appropriated from other regions is embodied in products imported from the Waikato region. Otago[211], Northland and Southland regions also make significant interregional contributions. Auckland Region's manufacturing sector is the greatest appropriator, accounting for some 87.6 percent of the land embodied in interregional imports. The size of the contribution made by Northland and Waikato regions is not surprising given that they are Auckland Region's closest neighbours. More influential, however, is the role these regions play in providing agricultural product to the Auckland Region food manufacturing industries. The rich pastures of the Waikato region support intensive farming, with 75.3 percent (1,500,000 ha) of its biologically available land in grazing, arable or fodder use. Similarly, Northland region is a major producer of sheep, beef and horticultural products.

[211] The size of the contribution is due primarily to the low productivity of much of the region's agricultural land. That is, agricultural products appropriated from Otago supporting Auckland Region's domestic consumption embodied far more land than similar products purchased from other regions.

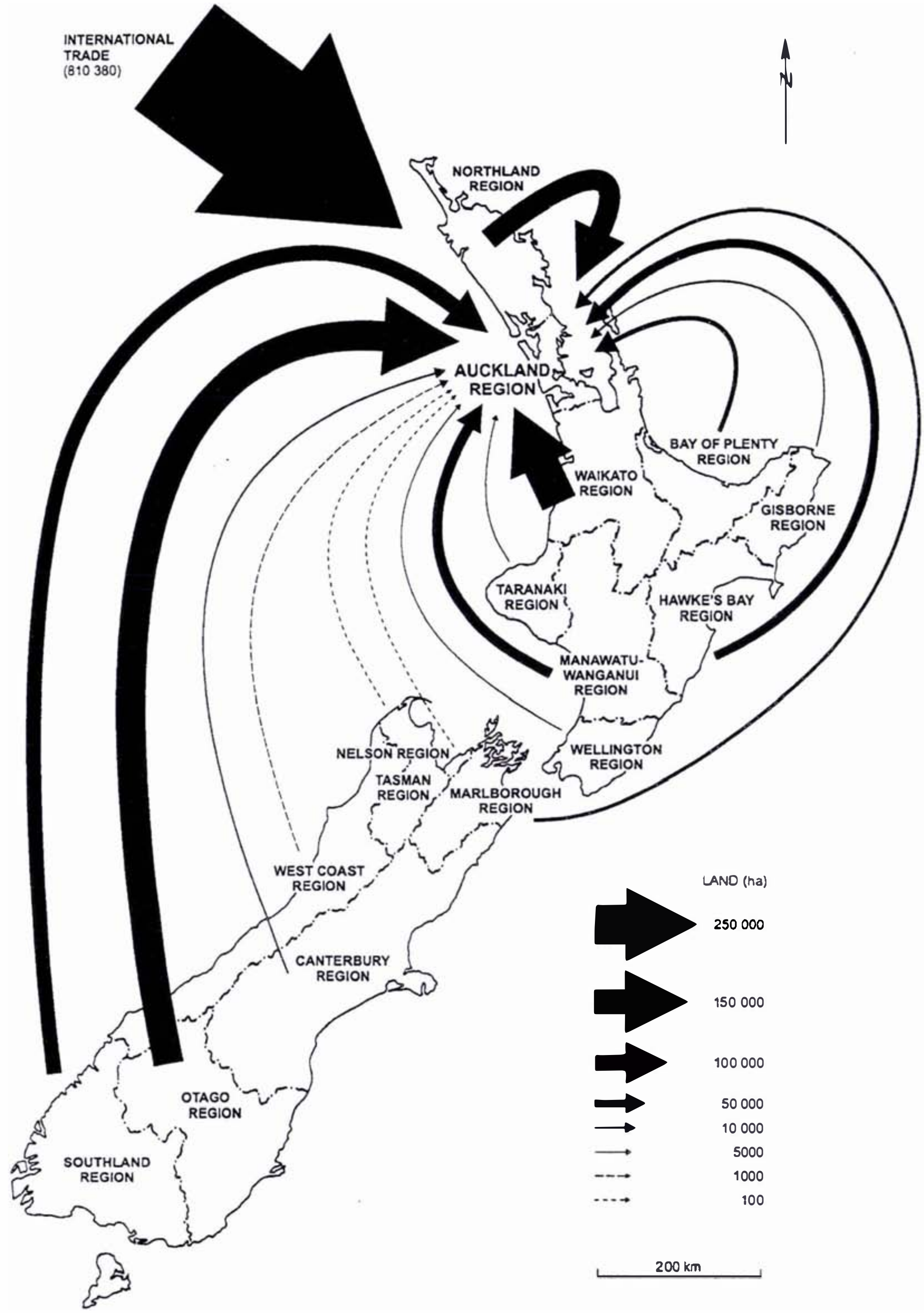

Figure 8.1 Regional and International Origins of Auckland Region's Ecological Footprint, 1997-98

The origins of forest land embodied in interregional imports reflects the spatial location of major planted forests in the North Island. The Waikato and Bay of Plenty regions form part of the largest planted forest area in New Zealand, mostly *Pinus radiata* although small plantings of Douglas fir and other varieties do exist. Lesser, but still significant, forest plantations also exist in the Northland and Gisborne regions. Auckland Region's sizable construction, printing and publishing, and other manufacturing sectors drive the demand for forest products from these hinterland regions.

8.4.6 Comparing Auckland Region's Ecological Footprint with Other Regions

The Auckland Region's Ecological Footprint is compared with other New Zealand regions in Figure 8.2. It shows in relative terms each region's actual land area (on the left) alongside its corresponding appropriated footprint area (on the right). Overall, Auckland Region has the largest footprint of any region, in excess of 1.3 times Canterbury, the next largest region.

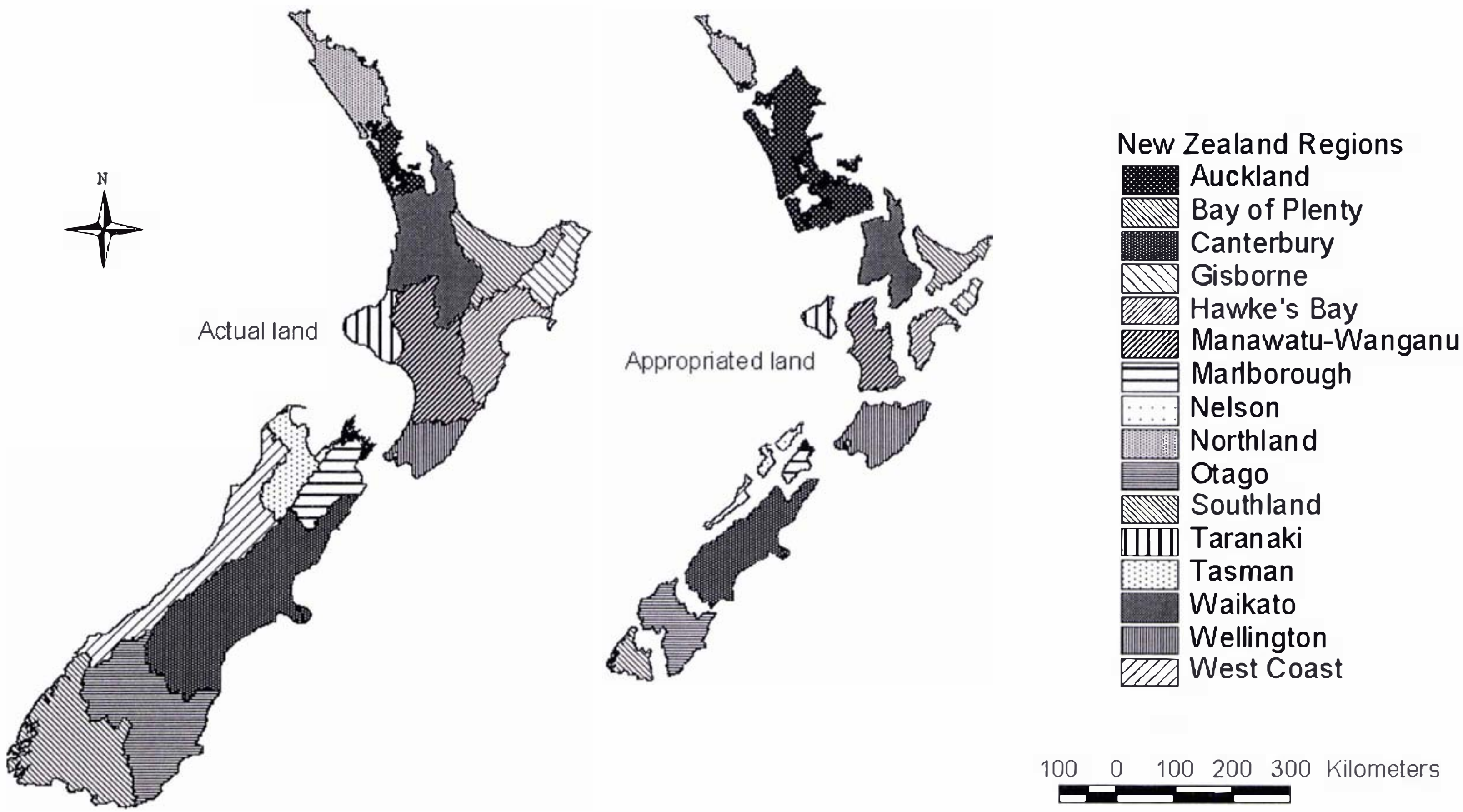

Figure 8.2 Ecological Footprints of New Zealand Regions, 1997-98

Auckland (2.00 ha per person) along with Wellington (2.40 ha per person), and Nelson (1.86 ha per person) are among the lowest per capita footprints in New Zealand (Figure 8.3). These are the three most urban regions in New Zealand, and this seems to be the main determinant of their low footprints. Urban settlement and consumption patterns are more efficient in their use of land – viz, land requirements per capita for retailing, housing, infrastructure and transport are considerably lower in urban areas compared with rural areas. There is also some evidence that urban transport requirements are relatively low, thereby reducing the size of the energy component of the ecological footprint for these – this is particularly so for Wellington that has an energy efficient public transport system based to a large extent on light rail.

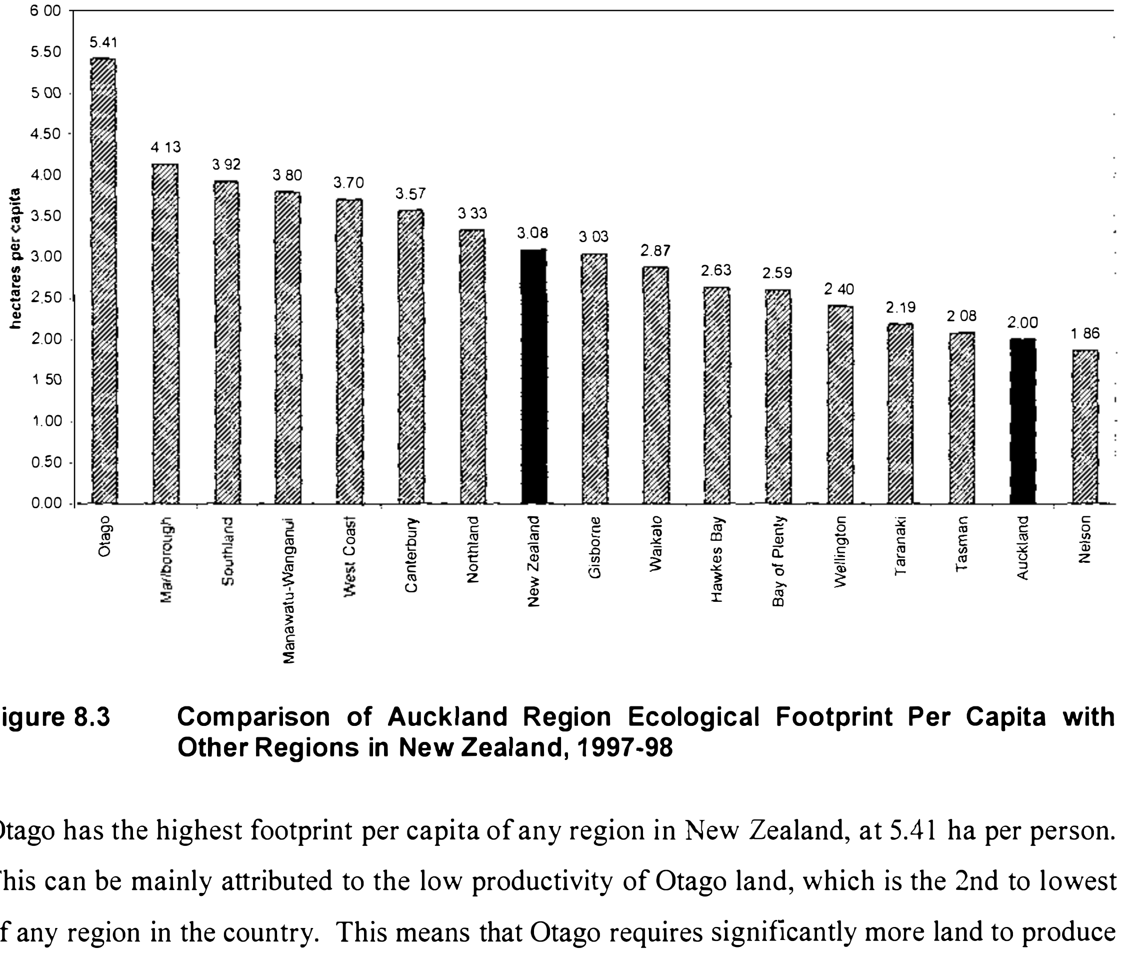

Figure 8.3 Comparison of Auckland Region Ecological Footprint Per Capita with Other Regions in New Zealand, 1997-98

Otago has the highest footprint per capita of any region in New Zealand, at 5.41 ha per person. This can be mainly attributed to the low productivity of Otago land, which is the 2nd to lowest of any region in the country. This means that Otago requires significantly more land to produce the same amount of output as other regions. Marlborough has the second highest footprint at 4.13 ha per person, again largely attributable to the region's low land productivity. Both of these regions also have relatively low population densities meaning that the spread-out nature of their settlement increases travel distances and hence the size of their footprints.

Southland (3.92 ha per person) and Manawatu-Wanganui (3.80 ha per person) rank 3rd and 4th in terms of the size of their per capita footprint. While parts of these regions are highly productive, other parts, particularly mountainous areas with harsh climates, have extremely low productivities. This is the main reason why these regions have reasonably high per capita footprints. Southland also has the highest per capita Energy Land footprint component of any region due to its colder climate.

West Coast (3.70 ha per person), Canterbury (3.57 ha per person), Northland (3.33 ha per person), Gisborne (3.03 ha per person) and Hawke's Bay (2.63 ha per person), all have footprints around the New Zealand average which would be expected on the basis of their land productivities.

Waikato (2.87 ha per person), Bay of Plenty (2.59 ha per person), Taranaki (2.19 ha per person), and Tasman (2.08 ha per person) all have per capita footprints below the New Zealand average. These regions have relatively high land productivities (ranked 1st to 4th). It is therefore not surprising that the per capita footprints of these regions are among the lowest. The spread-out nature of the Waikato and Bay of Plenty settlements, which are less urban than some other regions, may explain why the footprints of these regions are not lower than stated.

8.4.7 Comparing Auckland Region's Ecological Footprint with International Ecological Footprints

Auckland Region's Ecological Footprint can be compared with 1996 international footprint estimates produced by Loh (2000). This requires that Auckland Region's footprint be adjusted for: (1) global average yields[212]; (2) biological equivalence factors[213] and (3) the application of a global average CO_2 sequestration factor[214]. On this basis, Auckland Region's footprint of 5.68 ha per capita was found to be significantly smaller than both New Zealand (8.35 ha) and Australia (8.50 ha), slightly smaller than Japan (5.90 ha), but larger than South Africa (4.04 ha) and Argentina (3.80 ha) (refer to Figure 8.4).

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[212] Loh (2000) estimates New Zealand's average pasture yield factor to be 5.24, with the average yield factors for arable and forest land estimated to be 2.09 and 0.61 respectively. In the case of built-up land the average arable yield factor is applied.

[213] The following equivalence factors based on Loh (2000) were applied: for energy land 1.78, for arable land 3.16, for forest land 1.78 and for pasture land 0.39. The equivalence factor for arable land was used as a proxy for built-up land.

[214] Loh (2000) estimates the world average carbon absorption (including roots) to be 0.956 t ha^{-1}. In accordance with Loh (2000) oceans are also assumed to take up 35 percent of CO_2 emissions.

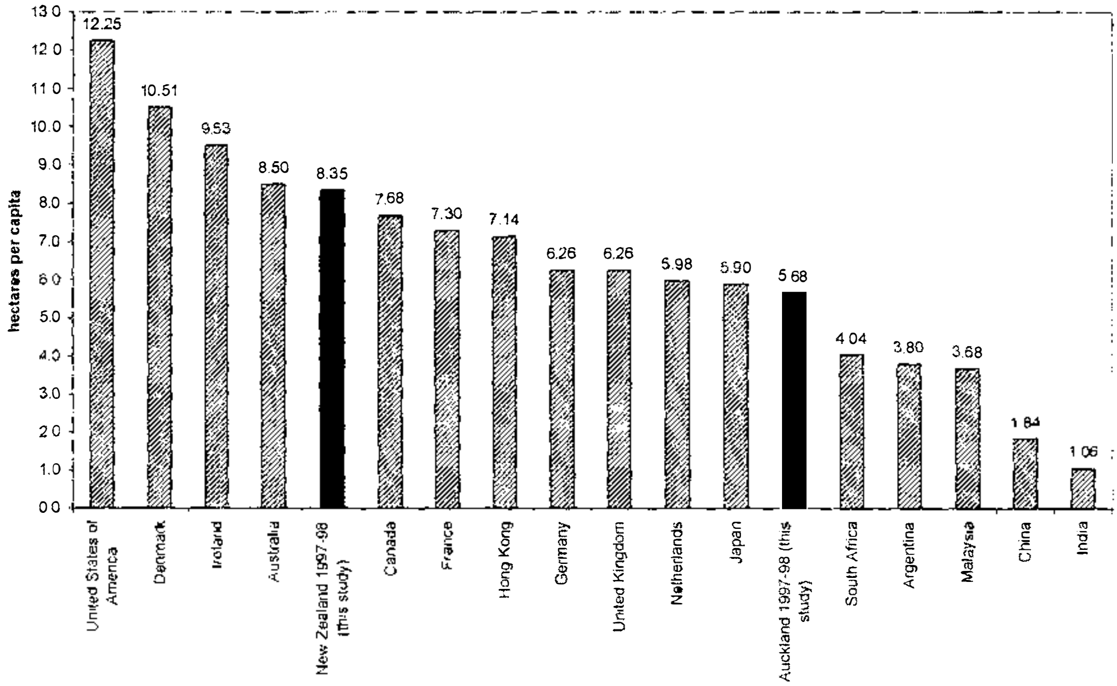

Figure 8.4 **Comparison of Auckland Region Ecological Footprint Per Capita with Other Nations**

PART III ENVIRONMENT-ECONOMY INTERACTIONS IN AUCKLAND REGION

A DYNAMIC SYSTEMS ANALYSIS

Chapter Nine

System Dynamics Approach to Modelling Ecological-Economic Systems

The system dynamics approach to modelling is used to construct the Auckland Region Dynamic Ecological-Economic Model (ARDEEM) in Chapter 11, and the Global Biogeochemical Cycling Model (GCBM) in Appendix B. In this current Chapter, the system dynamics approach to modelling is explained in general terms. The first two Sections focus on why we should build dynamic models and in particular system dynamics models. The next three Sections concentrate specifically on the history of system dynamics, the key features of system dynamics, and the general modelling process that should be followed when constructing system dynamics models.

9.1 Why Build Dynamic Models?

A significant limitation of many models is that they are static by nature, i.e. they represent a snapshot of reality at a single point in time. Reality, however, is not static, but constantly changing. It has a dynamic nature brought about by the interrelationships between all of its parts. Consequently, as explained in Chapter 4, static models provide only a limited understanding of reality. The quest for a more complete understanding of reality requires that we consider and examine dynamic interrelationships.

The primary distinction between dynamic and static models lies in their temporal scope. Static models represent phenomena at a single point in time, while dynamic models examine phenomena across time. This consideration of intertemporal linkages is emphasised by Hicks (1985, p.25), who argues that even at a point in time, "the links which relate the point to the rest of the dynamic process cannot be neglected". Dynamic processes are typified by feedback, where the response of the system to a stimulus may not be immediate, but delayed (Hannon and Ruth, 2001). Dynamic modelling acknowledges that real-world systems are open, and therefore cannot be adequately understood without reference to related phenomena that are outside the system. The consideration of interrelationships across time by dynamic models also "contains the potential for the derivation of theorems concerning the values of variables, or changes in those values" (Kuenne, 1963, p.14). A dynamic model would therefore be suited to a question such as, what are the potential environmental impacts of continued population growth in Auckland Region over the next 50 years?

Dynamic modellers such as Ruth and Hannon (1997) and Hannon and Ruth (1994, 2001) have outlined a number of reasons why dynamic modelling is of value: (1) intricacies of real world systems – real systems contain feedbacks, non-linearities, time lags and other complexities of interconnectedness which quickly overwhelm the human ability to comprehend these in a mental model; (2) simplification of complex phenomena – a model allows us to exclude certain phenomena we believe are superfluous to the system under study, in order to gain a clearer understanding of its complexity; (3) generation of new knowledge – dynamic modelling allows expansion and experimentation, facilitating 'what if' questions; (4) discovery of patterns in details, without losing the big picture – a dynamic model is as much about viewing the system as a whole, as it is about revealing underlying key processes or variables which may result in specific outcomes; (5) true abstractions of reality – in focusing on a particular set of details, we are forced to account for the results of the structural and dynamic assumptions underpinning the model; and (6) prediction of a future course – dynamic models are primarily about understanding, but a good model may facilitate forecasting by revealing gaps in our knowledge of the system, as well as the potential result of any future action.

9.2 Why Build a System Dynamics Model?

Wolstenholme (1990, p.3) defines system dynamics modelling as "a rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organisation boundaries and strategies; which facilitates quantitative simulation modelling and analysis for the design of system structure and control". Complex systems generate outcomes that are dependent on the continuous interaction between system components. A system dynamics model, in capturing these complex interactions, facilitates a more complete understanding of the dynamics of real-world processes. System dynamics modelling is thus a methodology for creating models of real world systems, with the aim of studying and managing the dynamic behaviour that results from complex feedback mechanisms (Wolstenholme, 1990; Ford, 1999).

Deaton and Winebrake (2000) explain several principal uses of system dynamics models. Firstly, system dynamics modelling is aimed at developing an understanding of the processes and mechanisms underpinning a system and how it functions. Those mechanisms that either maintain or jeopardise a system's stability are revealed. Secondly, a good system dynamics model will allow prediction of future system behaviour. The modelling process reveals cycles and trends, allowing the implications of different decisions on system stability to be studied. Thirdly, system dynamics modelling allows experimentation, without affecting the real system.

Fourthly, system dynamics modelling raises additional questions about the system, its behaviour, and its applicability to understanding other systems.

Other modelling techniques, such as econometrics, Computable General Equilibrium (CGE) and optimisation modelling, should not be confused with system dynamics modelling. Econometric modelling, most commonly used in macroeconomic analysis, employs statistically independent variables to describe a dependent economic relationship, obtaining an indication of the relative influence of each of the variables (Bannock *et al.*, 1992). These models are suited to prediction over the short to medium term and are often based on historical information. Econometric modelling, unlike system dynamics, does not take into account any interrelationships or feedbacks between the variables (Sterman, 1991). While CGE models temporal change, this is typically comparative static rather than truly dynamic, in that it does not account for intertemporal relationships and feedbacks between system components. Optimisation modelling is a technique where choices are made regarding specific goals and constraints to be satisfied. A system dynamics model, in contrast, rarely maximises any one variable (Ryan, 1995).

9.3 Brief History of System Dynamics

The field of system dynamics had its early beginnings in 1956 at the Massachusetts Institute of Technology (MIT), when Jay W. Forrester in his seminal book, *Industrial Dynamics* (1961), applied feedback control concepts to industrial systems (Ford, 1999). Around the 1970s, the use of system dynamics models broadened with the publication of Forrester's (1969) *Urban Dynamics*, and Meadows *et al.*'s (1972) *Limits to Growth.*

Urban Dynamics generated wide-spread controversy through what appeared to be counter-intuitive proposals for combating urban stagnation and decay in several major US cities (Richardson and Pugh, 1981; Alfeld, 1995). The model analysed the dynamic interactions between industries, housing and people. As the population grew, and housing demand escalated, the increasing scarcity of land for industrial purposes set in motion stagnation and eventual decline of some urban areas. Forrester (1968) noted that conventional planning policy met housing demand at the expense of industry growth, which resulted in job scarcity and, in turn, stagnation. To reverse the onset of urban decline, he advocated a policy change away from further investment in low cost housing to slum demolition.

Limits to Growth (Meadows *et al.*, 1972) is perhaps the most well-known system dynamics study undertaken to date. This study, commissioned by the Club of Rome, focused on the impacts of future exponential population growth in a world of finite natural resources (Richardson and Pugh, 1981; Ford, 1999). The study warned that attempts to overcome the ecological constraints imposed on sustained population and economic growth would lead to significant capital and labour diversion (Meadows *et al*., 2004). Under certain assumptions it predicted that by the mid twenty-first century there could be a significant decline in quality of life – even possibly a collapse of the global economic system. The goal of *Limits to Growth* was not to forecast doom and gloom however, but to increase understanding of the global system (Ford, 1999). Experimentation with alternative scenarios led the study's authors to conclude that, "it is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future" (Meadows *et al*., 1972, p.24).

9.4 Key Features of a System Dynamics Model

Some of the distinguishing characteristics which may be captured by a system dynamics model are:

- *Intertemporal*. Reality is not static but constantly changing through the ongoing interactions between all of its parts. System dynamics models capture such complex changes across time.
- *Non-linearities*. Dynamic systems exhibit complex behaviour such as exponential growth and decay, oscillatory patterns and overshoot and collapse.
- *Feedbacks*. Dynamic system components interact with each other through feedbacks, i.e. one component stimulates changes in other components, which in turn affect the first component. Negative feedback counteracts the initial change, while positive feedback reinforces the initial change.
- *Time lags*. The response of a dynamic system to a stimulus may not be instantaneous, but delayed. The introduction of time lags into a dynamic model typically results in oscillatory behaviour. Numerous time lags often make it extremely difficult to predict or control a system's behaviour.
- *Endogenous variables*. System dynamics models aim to have as many variables as possible calculated by the model structure itself (i.e. internalised into the model), rather than having exogenous variables that critically affect model performance (Ryan, 1995).
- *Learning, testing and experimentation*. System dynamics models allow variables to be changed iteratively to investigate possible outcomes without affecting the real system.
- *Diagrammatic representation*. System dynamics models make use of conceptual diagrams, based on a stocks and flows analogy, as the medium for transmitting

information and discussing change. Diagrams provide a less ambiguous, condensed, and more digestible form of communication.

A system dynamics model can never capture all of the features of a real system. One of the most important features of non-linear systems is that even infinitesimal changes in initial conditions or in system specifications can cause unbounded changes in trajectories. This has been termed the 'butterfly effect', from the idea that even the fluttering of butterfly wings in the Amazon forest might have some unpredictable future impact on the weather in Chicago (Ayres, 1996). Thus, it is virtually impossible for modellers to determine all of the features of the dynamics of a system – in the end, the only adequate model of a system is itself.

9.4.1 Dynamic System Behaviour

In this Section five common behaviours of dynamic systems are described, namely: linear growth or decay, exponential growth or decay, logistic (S-shaped) growth, overshoot and collapse, and oscillation.

Linear Growth or Decay

A state variable (or stock) displays linear behaviour if it increases or decreases at a constant rate over time (Figure 9.1a). Growth will occur if the linear constant is positive, decay if negative, and no change if zero. The constant also represents the slope of the graph depicting the change in stock over time. A linear system can only achieve a steady state if the constant is zero. A system displaying linear behaviour therefore contains no feedback.

Exponential Growth or Decay

Exponential growth (or decay) is characteristic of a stock that increases (or decreases) in proportion to its size (Figure 9.1b). A system exhibiting exponential behaviour must incorporate positive feedback, where a change in a stock increases (or decreases) the size of the stock, which in turn reinforces the change. The greater the rate of change, the more rapid the exponential growth or decay.

Logistic (S-shaped) growth

A system displays logistic growth if it initially exhibits exponential growth, but is then constrained by limits, forcing the growth to level off. The resultant curve (Figure 9.1c) is **S-**

shaped. This type of growth is typical of biological populations, for example, whose growth is limited by available food or nutrient supply (Ford, 1999).

Overshoot and Collapse

A system will display overshoot and collapse behaviour where a stock of, say, a population, is dependent on a resource stock for survival (Figure 9.1d). As population grows, it will consume and exhaust the resource stock to the point where the population stock can no longer be maintained and eventually collapses.[215] Often the growth of the population stock may not slow down as it approaches the limit imposed by the resource stock, as the effects may not be immediately felt, resulting in a peak in the population stock followed by sudden collapse (Ford, 1999). In this way, the rate of change in each stock is dependent upon the size of the other.

Oscillation

A system will exhibit oscillatory behaviour where there is a strong negative feedback that causes it to cycle around an equilibrium condition (Deaton and Winebrake, 2000). A classic example is the predator-prey relationship, where an increase in the predator population causes a decrease in the prey population, leading to a subsequent decrease in predators, in turn, resulting in an increase in prey (Figure 9.1e).

Ford (1999) groups oscillatory behaviour according to four major patterns: (1) sustained oscillations which continue indefinitely at the same amplitude and period; (2) dampened oscillations which exhibit no change in period, but a declining amplitude over time; (3) growing oscillations which indicate an unstable system, with the amplitude increasing with each successive oscillation as the system moves further away from its starting point; and (4) limit cycles which indicate repetitive oscillations of a system that is restricted in its movement, causing the usually symmetric cycles of the system to become irregular.

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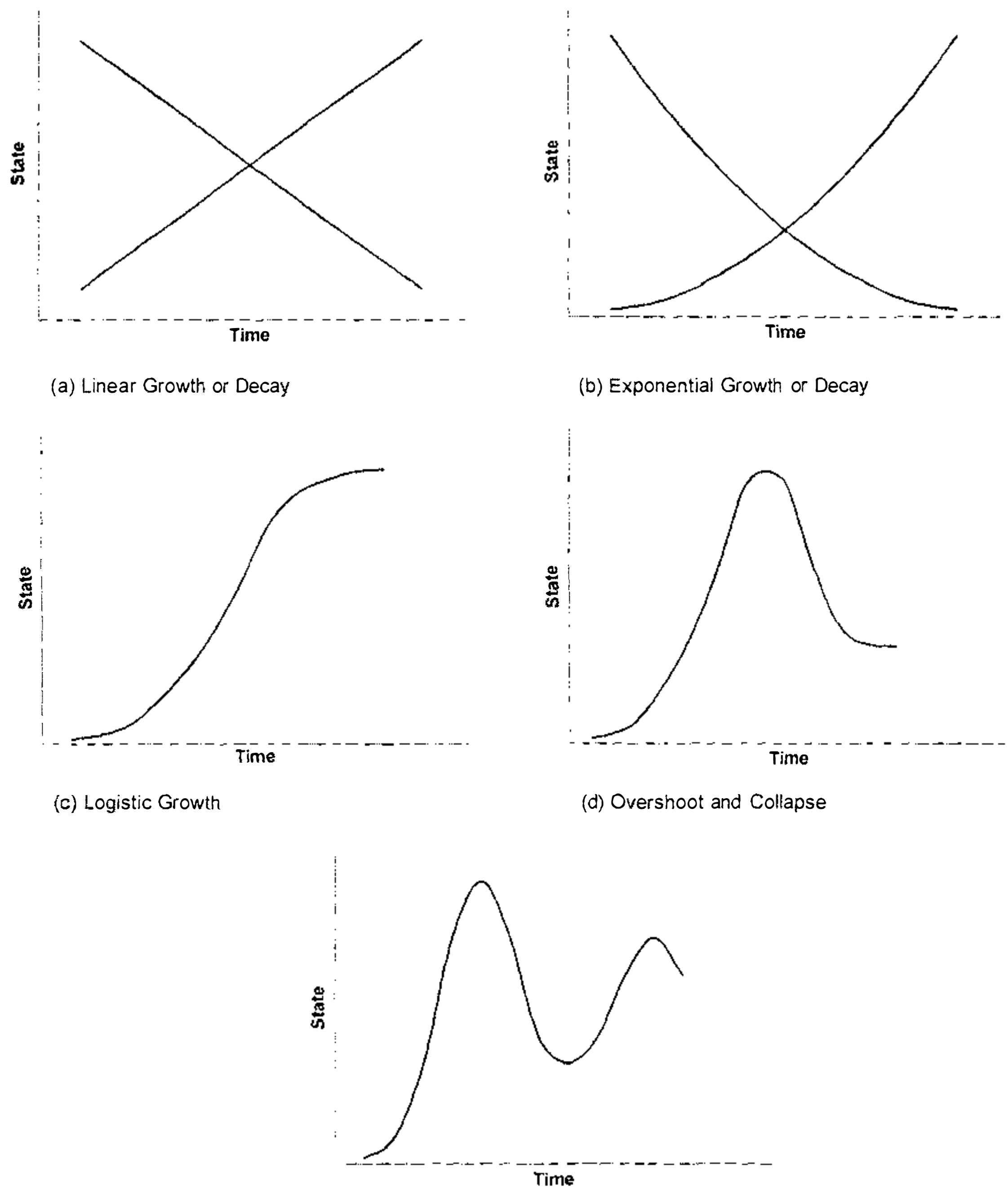
[215] This situation is typical of a non-renewable resource. Overshoot and collapse of a population stock may also be observed when a renewable stock is depleted at a rate faster than its regeneration rate (Deaton and Winebrake, 2000).



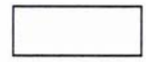
(e) Oscillation

Figure 9.1 Common Types of Dynamic Behaviour

9.4.2 Building Blocks for System Dynamics Models

In this Section the four basic building blocks for designing a system dynamics model are described, stocks, flows, converters and connectors. These building blocks are shown in Table 9.1.

Table 9.1 Four Systems Components and their Modelling Symbols

Name	Description	Symbol
Stocks	Principle variables in the model, representing accumulation or storage in the system, and possibly fluctuating over time	
Flows	Variables directly affecting stocks and determining their values over time	
Converters	Govern the rate at which flows operate and stocks change	
Connectors	Define the cause-and-effect relationships between system entities	

9.4.2.1 Stocks

Stocks, also called levels, reservoirs or state variables, are the principal variables in the model, ultimately determining the dynamic behaviour of the system (Hannon and Ruth, 1997; Vensim® Reference Manual, 1999). They represent accumulation or storage in the system (Ford, 1999; Deaton and Winebrake, 2000). Stock variables indicate the current status of the system and can only change over time dependent on the value they, along with other variables, had at previous times (Hannon and Ruth, 1997; Vensim® Reference Manual, 1999). Two simple questions may aid in the identification of stocks: (1) are there key entities in the system that could accumulate or diminish over time?, and (2) if the flows were zero, what variables would remain unchanged at their current values? In order to preserve simplicity in the model, an attempt should be made to keep the number of stock variables to a minimum (Hannon and Ruth, 1997). The size of a population under study is an example of a stock in a population model. Stocks are depicted graphically in the model as rectangles.

9.4.2.2 Flows

Flows, also called processes, rates or control variables, are the variables that directly influence the stocks (Hannon and Ruth, 1997; Vensim® Reference Manual, 1999). While stocks indicate the status of the system at a point in time, the flows are an ongoing process, changing the size of the stocks to take the system to a different state in the future. The value of the flow expresses the amount of change it causes to the stock in one full-time unit, updating the stock variables at the end of each time step (Hannon and Ruth, 1997; Deaton and Winebrake, 2000). Examples of flow variables in a population model are birth inflows and death inflows. Flows are represented graphically as a double-lined arrow that flows into and/or out of a stock. A cloud located at the end of a flow may be viewed as a stock that resides outside of the system boundary.

9.4.2.3 Converters

Converters, or auxiliaries, are added to the model to describe the flows. The most important function of a converter is to govern the rate at which the flows operate, and accordingly, the rate at which stock sizes change (Ford, 1999; Deaton and Winebrake, 2000). Converters may also be utilised in the calculation of indicators of system performance. In a population model, the birth rate converter regulates the birth flow, in turn altering the size of the population stock over time. A converter is represented graphically in the model as a circle.

9.4.2.4 Connectors

Connectors, or interrelationships, indicate the information flow within a model, defining the cause-effect relationships between elements in the system (Ford, 1999; Deaton and Winebrake, 2000). In a population model, for example, the interrelationship between the birth flow, the birth rate converter, and the size of the population stock can be expressed in the following simple mathematical equation (Deaton and Winebrake, 2000),

$$b = 0.2 \times R(t), \tag{9.1}$$

where b is the number of births, 0.2 is the birth rate, and $R(t)$ is the size of the population in year t. Graphically, connectors between causal and affected entities are represented by arrows.

9.4.2.5 Bringing the Building Blocks Together

With connectors in place, mathematical expressions may be derived to explain the calculation of each quantity in the model at each point in time (Deaton and Winebrake, 2000). Using mathematical variables, let $R(t)$ denote the size of stock R at time t. Because a flow represents the change in the stock size in one full-time period, we calculate the future stock one period ahead as,

$$R(t+1) = R(t) + (\text{sum of all inflows} - \text{sum of all outflows}), \tag{9.2}$$

and the stock R at a point in time in the future, dt, as

$$R(t+dt) = R(t) + (\text{sum of all inflows} - \text{sum of all outflows}) \times dt. \tag{9.3}$$

This equation, known as the difference equation for stock $R(t)$, calculates future values of a stock from its previous values.

For system entities (e.g. stocks, flows, converters) with incoming connectors or flows, the manner in which inputs will be used to calculate their values will be defined by the modeller. An entity without flows or connectors entering it must have an exogenous value determined by the modeller as an initial condition. When the mathematical relationship between an entity and the variable that determines it is not readily apparent, converters are often presented in graphic format – the shape of the relationship defining the system entity.

Information flow may take the form of a feedback, either negative or positive, flowing in a loop from the stock through a succession of transforming entities, back to the flow, causing a change in the stock over time (Hannon and Ruth, 1997). Negative feedback, the basis of a controlled dynamic system, tends to restrict stock variables to limits established either implicitly or explicitly within the model. Through negative feedback, a change occurs that makes further change less likely. By contrast, positive feedback amplifies rather than minimises differences, causing change in a direction that makes further change more likely (Clayton and Radcliffe, 1997; Hannon and Ruth, 1997). The complex dynamic behaviour in a system dynamics model is typically the result of feedback processes, where a control variable is dependent on another variable that exhibits non-linear behaviour.

9.4.2.6 General Principles for Building Systems Models

The basic process for building a systems model is to begin with stocks, add flows, and then finish the model with converters. Deaton and Winebrake (2000) present a list of five guiding principles for successful systems model design: (1) begin with a simple model, adding complexity only as and when necessary; (2) use reasonable mathematical equations to define system relationships; (3) where a satisfactory equation is not readily apparent, use graphs to depict relationships; (4) select appropriate units of measurement for both time and the system entities, ensuring that all units are consistent with previously defined equations[216]; and (5) make sure that only inflows and outflows have any direct influence on stock values.

[216] Forrester (1961) stressed the importance of precise and consistent use of units for all variables and constants, warning that confusion may easily arise from carelessness in this regard. Furthermore, he noted that dimensionless variables, typically formed as the ratio of two numbers expressed in the same measurement units, often play an integral part in equation formulation.

9.4.2.7 Setting Delta Time

In the model, the calculations are carried out repeatedly over small time increments, *dt*, to cover the desired time interval. In selecting *dt*, a useful guide is to find the shortest time constant in the model, and then to set *dt* to half of its value. Systems containing both short and long time constants (or 'stiff' systems) require specially designed integration methods (Pugh-Roberts Associates, 1986; Shampine and Gear, 1979; Ford, 1999). Short time constants necessitate selection of a small *dt* value, while long time constants require that the model be simulated over a long time interval.

9.4.2.8 Hannon and Ruth's Four Model Set

Hannon and Ruth (2001) have prescribed four basic model forms that underpin a variety of different modelling processes (Figure 9.2). The first is the stimulus-response form, Figure 9.2(a). A flow into a stock, for example, is independent of the value of the stock, i.e. the condition of the stock has no influence on the flow as there is no feedback relationship between these two entities. The additional stock arriving via the flow creates a stimulus for change.

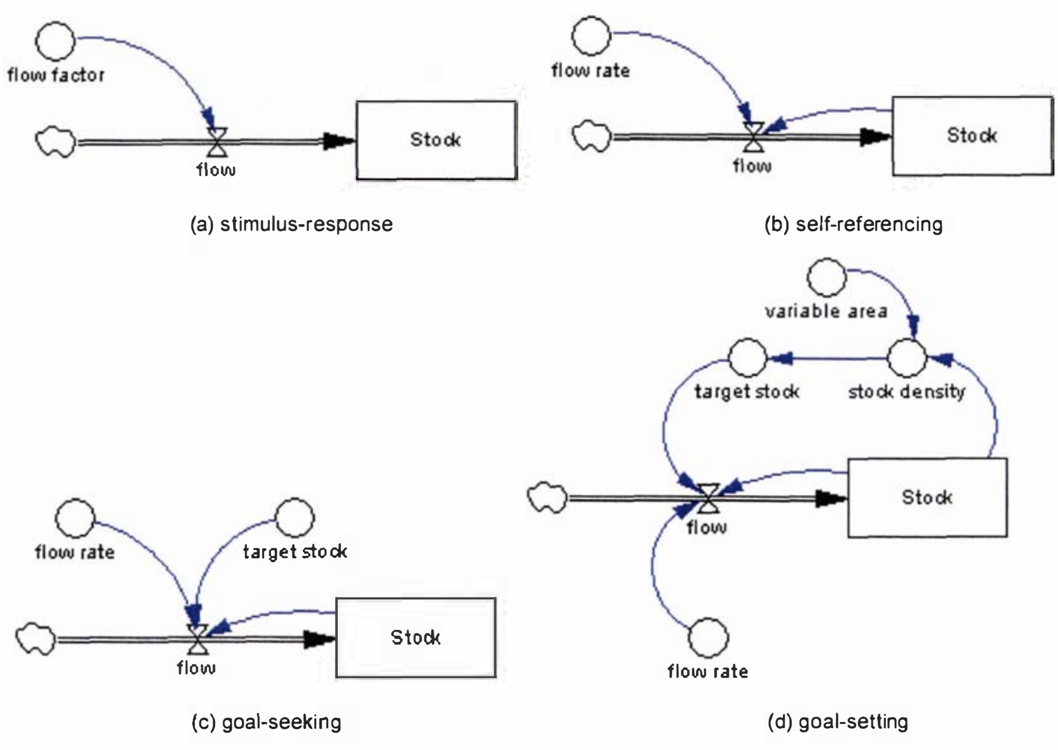


Figure 9.2 Hannon and Ruth's Four Model Set

The second basic form is the self-referencing model, Figure 9.2(b). Here the level of the stock, for example, influences the inflow, and therefore determines its own growth, i.e. there is a feedback relationship between the stock and the flow such that the flow is dependent on the level of the stock.

The third form is the goal-seeking model, Figure 9.2(c). In this model the stock value is determined by a target value, and as long as there is a difference between the current value and the target value, the stock will be driven toward the target value. In this way, a flow into a stock, for example, depends not only on the value of the stock, but also on an exogenous target value.

The fourth basic model is the goal-setting model, Figure 9.2(d). Here, not only does the stock influence its inflow, but also, along with one or more external variables, its own target value.

9.5 Modelling Process

The key steps in the modelling process are depicted in Figure 9.3 and explained in detail below.

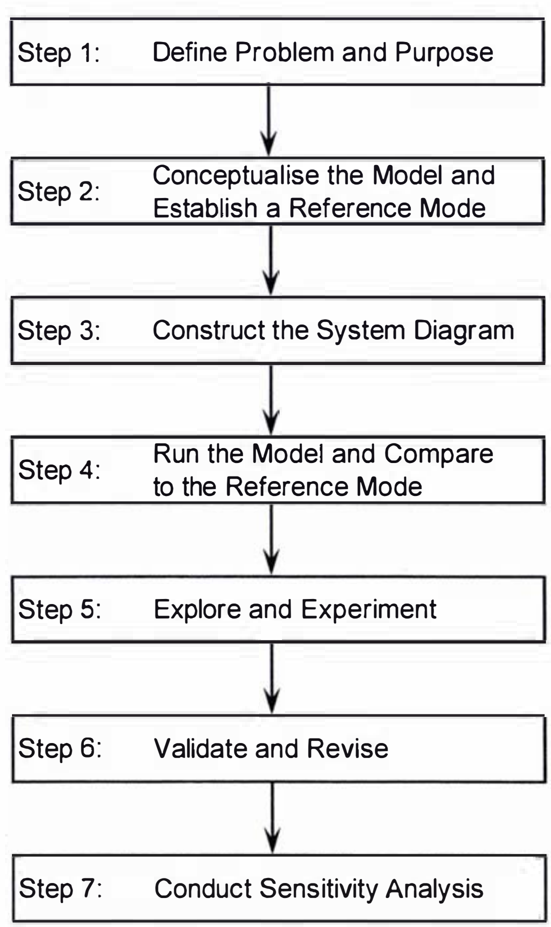


Figure 9.3 Key Steps in the System Dynamics Modelling Process

Step 1 Define the Problem and Purpose

Since a model will typically be constructed to deal with a specific problem, a critical early task is to clearly define the problem. Deaton and Winebrake (2000) recommend development of a clear purpose statement that will help focus model development by identifying the system under investigation, the key entities that comprise the system, key system behaviours to be understood, and the key questions to be answered. Setting the questions to be answered is arguably the most important step and will help keep the modeller focused. This questioning process is ongoing, iterative, and is often the most critical success factor in system dynamics modelling.

Step 2 Conceptualise the Model and Establish a Reference Mode

System dynamics models are used for studying structural rather than categorical complexity. A categorically complex system is typically data-rich, has an extensive set of inputs and contains no feedbacks. By contrast, a structurally complex system will contain feedback loops, non-linearities and the like, all of which lead to dynamic behaviour. Conceptualising this behaviour requires that only significant stocks and flows and their associated interrelationships in the real system be captured in the model. This includes consideration of key variables to be endogenised, as well as less relevant, or static, exogenous variables.

Ford (1999) suggests conceptualising the model in a bull's-eye diagram (Figure 9.4) with the centre reserved for crucial endogenous variables, and the outer ring for less influential exogenous variables. Any variables beyond the outer ring are excluded from the model. The bull's-eye is a useful tool for clarifying system boundaries, as well as for depicting models that are too complex for representation in a flow diagram. A diagram with only exogenous variables, and hence no feedback, would not represent a dynamic model. This conceptualisation of the model captures interactions among the most important variables. A balance needs to be struck between making the model more complex and hence closer to reality, and keeping it simple for ease of analysis and understanding.

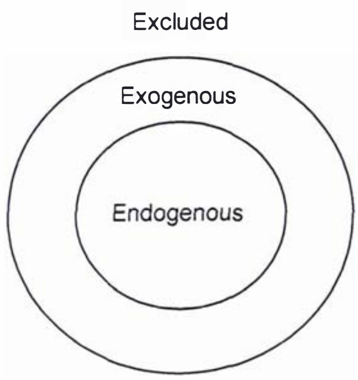


Figure 9.4 Bull's Eye Diagram

Once the model has been conceptualised and defined, a reference mode should be established. This should be in the form of graphs depicting important system variables on the vertical axis, and their predicted change over time on the horizontal axis. This is an important step that should occur before the actual analysis begins. The graph of a given variable is likely to conform to one or more of the dynamic patterns outlined in Section 9.3.1.

Step 3 Construct the System Diagram

The first stage in this step entails construction of the stock-and-flow diagram. The stock variables are selected first as these will indicate the status of the system as it changes through time (Hannon and Ruth, 1997). The flow variables should be added next. It is important to note whether the flows are inflows into, or outflows from, the stocks (Hannon and Ruth, 1997). Once the flows are identified, the converters can be added. At this stage the model should be kept simple; complexity will be added in later steps. In addition, numerical formulae for the calculation of the flows must be determined.

Once the stock and flow diagram is composed, various consistency and error checks need to be carried out. The units for all variables, as well as any conditional statements such as non-negativity or division by zero, must be specified (Hannon and Ruth, 1997). The diagram should also be scrutinised for any violations of appropriate laws e.g. the physical law of conservation of mass. Hannon and Ruth (1997) recommend that construction of the diagram be concluded with a graph depicting the key variables, from which predictions can be made regarding system behaviour before running the model.

Step 4 Run the Model and Compare to the Reference Mode

Before the model is run, initial conditions and *dt* need to be specified. There may be some variable values which are uncertain or simply unknown, requiring the modeller initially to select an intuitive value. It is very important that uncertain variables are not simply eliminated from the modelling process as this effectively sets them to zero (Forrester, 1968; Ford, 1999). The model will go through several iterations making it possible to revise variables when necessary (Hannon and Ruth, 1997).

This is the first occasion for the model to be tested. The results should be compared to the reference mode and checked for sense. It is important to remember that modelling is an iterative trial-and-error process, each time leading to further refinement. Ford (1999) notes that successful modellers will agree that the modelling process is often more important than the actual model itself, with each iteration increasing understanding of the system.

Step 5 Explore and Experiment

Once the model has been run for the first time, it should be experimented with to explore the system's response to changing conditions (Deaton and Winebrake, 2000). This is not necessarily to establish the ideal conditions for system performance, but to develop a better understanding of the effect of the various components on system behaviour. The system's response to changing stimuli is determined by the dynamics of the system, where a change in one or more elements can lead to dramatically different system responses which are not easily predicted. At this point greater structural complexity can be introduced into the model by expanding the set of endogenised variables in reflection of the results obtained.

Deaton and Winebrake (2000) suggest that the following information should be able to be ascertained after a thorough exploratory analysis: (1) the role each system component plays in overall system behaviour; (2) which individual components have the greatest effect or the least influence on the overall system; (3) which combinations of components appear to have a particularly large effect on the system; (4) the behaviour of the system when perturbed; and (5) the conditions under which the system may collapse or run out of control. Steps 1 to 5 of the modelling process should be repeated again and again taking into account any new insights gained during this exploratory phase. Modelling is an iterative process of running, revising, comparing and changing, with each iteration providing greater insight into system behaviour (Checkland, 1981).

Step 6 Validate and Revise

A model is valid if its portrayal of system behaviour adequately reflects the behaviour of the real-life system it is studying (Deaton and Winebrake, 2000). Hannon and Ruth (1997), however, remind us that complete verification of a model by comparison with the real world is not possible, as a model by nature includes only a selected number of components and behaves purely in response to its internal relationships. The model therefore becomes closed while the real system, in contrast, is open. Authors such as Hannon and Ruth (1997, 2001), Ford (1999) and Deaton and Winebrake (2000) suggest that the model be checked for both structural validity and predictive validity. Structural validity refers to the logic, consistency and accuracy of the model's internal structure, i.e. its equations, units of measurement and interrelationships. Predictive validity refers to the model's ability to adequately imitate the behaviour of the real system[217]. Sterman (1984) stresses that there is no absolute test for model validity – rather than valid, a model could be described as useful, insightful or convincing. Similarly, Checkland (1981, p.173) states that "there are not valid models and invalid ones, only defensible conceptual models and ones which are less defensible".

Step 7 Conduct Sensitivity Analysis

The model should be run several times with variations in the parameter values, the aim being to check whether the results are sensitive to changes in uncertain parameters and initial values (Hannon and Ruth, 1997; Ford, 1999). After experimenting with the parameters across the full range of uncertainty, but within reasonable extremes, the result should be compared with the reference mode – if it compares favourably, the model is considered to be robust. Kitching (1983) argues that highly uncertain parameters should be treated circumspectly with their role in the model evaluated using sensitivity techniques. Richardson and Pugh (1981) note however that the amount of effort put into determining such parameters should be commensurate with the sensitivity of the system to changes in these parameters.

Deaton and Winebrake (2000) categorise variables according to their degree of impact in the model. High-leverage variables have a significant impact on the model's behaviour and as such their values should be carefully validated. These variables provide the best opportunities to make a direct impact on the real-life system through intervention. Low-leverage variables, in contrast, have a minimal impact on system behaviour and do not need such careful validation.

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[217] The problem here is that it is quite possible to get an extremely good historical data fit from a model, but the future it simulates may still be incorrect.

They allow options for intervention that may not directly affect the system, but may have other important benefits.

A sensitivity analysis (Deaton and Winebrake, 2000) involves the following steps: (1) identify initial conditions and other exogenous variables in the system; (2) make a series of model runs for each exogenous variable, changing the value of the variable slightly[218] for each run; (3) evaluate the system behaviour after each run, determining the extent to which system behaviour changes in response to the change in each exogenous variable; and (4) identify high and low leverage variables, attempting an explanation for the influence a particular variable exerts on the system.

[218] The range of values adopted should reflect those likely to operate in the real system.

Chapter Ten

Critical Review of Growth Theories

This Chapter describes and critiques the main theories of economic growth, namely: classical growth theory, neo-classical growth theory, new 'endogenous' growth theory and other growth theories. Technological change is identified as the key determinant of ongoing economic growth. Under neo-classical growth theory technological change is treated as an exogenous variable, while new growth theory attempts to endogenise technological change through the careful consideration of the economics of ideas, in particular, how ideas are invented, how innovation occurs, and how ideas are diffused. It is shown that with technological change it is possible to generate increasing returns to scale. Nevertheless, it is argued that much of the research effort conducted to date on growth theory has proceeded without any consideration of possible biophysical or thermodynamic constraints. Once adjusted for these concerns, growth models exhibit diminishing returns to labour and capital, although it can be shown that technological progress has the potential to offset these effects. A race therefore exists between the increasing returns of technological advancement and the diminishing returns of resource scarcity/environmental degradation.

10.1 Classical Growth Theories

Growth theory is at least as old as Quesnay's (1763) *Philosophie Rurale*. At the time Quesnay believed the population of France had been in steady decline from a mid 1650 population of around 24 million, to 19.5 million in 1701 and, in turn, to 16 million in 1758 (Eltis, 1984).[219] Quesnay was interested in explaining how this decline had influenced French economic output and wealth, and in particular how the trend might be reversed. Using his *Tableau* he argued that France could at most sustain a population of 30 million (Eltis, 1984). The focus of his growth theory was on the rate of growth/decline of annual agricultural advances and incorporated the propensity to consume agricultural products, taxation rates, and rates of return and reinvestment. Thus, his attention was directed at understanding the underlying *causes* of (agricultural) economic growth/decline – an approach largely ignored by the later neo-classical growth theorists.

[219] Modern research suggests that this decline was less rapid than Quesnay believed (Eltis, 1984).

Adam Smith (1953/1776) in *An Inquiry into the Nature and Causes of the Wealth of Nations* introduced into economics the notion that increasing returns could be generated in manufacturing through specialisation and division of labour (Thirlwall, 2002). This was the complete converse of Quesnay and the Physiocrats who believed that only agriculture produced an investable surplus (Barbier, 1989). Moreover, the possibility of increasing returns offered the prospect of higher living standards for all. Central to Smith's theory of growth is a positive association between capital accumulation and productivity growth (Eltis, 1984; Barbier, 1989; Thirlwall, 2002).[220] Smith argued that capital accumulation led to increased population and employment, providing the necessary market for manufactured products – and possibly a 'widening' of the market. If competition was sufficient then market widening would lead to: (1) an increased division of labour and a resultant increase in productivity, and (2) an increase in the range and quality of manufactured products (Thirlwall, 2002).[221]

The prevailing classical view following Smith was largely pessimistic about the process of economic growth – the sentiment was so strong that Scottish philosopher Thomas Carlyle labelled economics the 'dismal science'. Thomas Malthus, in *An Essay on the Principle of Population* in 1798, advocated that "population, when unchecked, increases in a geometric ratio [while] ... the means of subsistence increases in an arithmetical ratio" (Eltis, 1984, p.15). Malthus concluded that an increasing population must therefore result in 'diminishing returns' to agriculture, the key consequence of which would be a dramatic decline in the standard of living. David Ricardo, in his *Principles of Political Economy and Taxation* in 1817, also asserted that diminishing returns to agriculture would lead to an economic stationary state and therefore no growth (Eltis, 1984; Thirlwall, 2002). The Ricardian argument is as follows: capital accumulation is determined by profits. Profits, however, are reduced by wages and land rent payments. Land rent payments increase with the higher food prices due to land-based diminishing returns. Industry profits also fall as a consequence of a lesser investment in capital products by wage earners. As profits fall to zero, capital accumulation ceases, leading to a stationary state (Thirlwall, 2002).

Both Malthus and Ricardo suggested that technology might offset diminishing returns (Paglin, 1961; Barnett and Morse, 1963; Common, 1988; Barbier, 1989; Lee, 1989; Coombs, 1990; Tisdell, 1990). Malthus concluded that with technological improvement "diminishing returns in agriculture were not a problem which need concern anyone for hundreds of years" (Paglin, 1961, p.83). Ricardo further suggested that technology might substitute for labour, thus

[220] This association has been overlooked by subsequent Keynesian and neo-classical economists who argue that capital accumulation has no long-run influence on the rate of economic growth.
[221] This conception of growth is similar to the 'learning-by-doing' model proposed by Kenneth Arrow in the early 1960s (Eltis, 1984; Thirlwall, 2002).

permitting sustained agricultural output. Nevertheless, both argued that population expansion would necessitate a dependence on labour rather than capital, crowding out technological innovation, and leading to diminishing returns in agriculture (Fischer, 1981; Samuelson and Nordhaus, 1985; Common, 1988, 1995; Barbier, 1989; Kula, 1994). Thus, in the long run both Malthus and Ricardo doubted that technological progress would completely offset diminishing returns.[222]

Central to classical economics is the generation of an economic surplus. It is the reinvestment of this surplus that is the primary determinant of the rate of economic growth in classical theory (Eltis, 1984; Barbier, 1989; Thirlwall, 2002). It is argued that increasing the fraction invested in capital accumulation must therefore increase the rate of growth. Increasing the fraction invested does not however result in an increased output per worker unless there is a complementary increase in worker productivity (Ryan, 1995; Thirlwall, 2002). This insight was to play a critical role in the development of a neo-classical growth theory.

10.2 Neo-classical Growth Theories

10.2.1 Harrod-Domar Growth Model

The work of Roy Harrod (1939, 1948) and Evsey Domar (1946) reignited interest in growth economics[223], providing a platform for the growth debates that would preoccupy economics from the mid 1950s to the mid 1980s (Solow, 2000; Thirlwall, 2002; Panico, 2003). Working independently they asked essentially the same question: "under what circumstances is an economy capable of steady-state growth?" (Solow, 2000, p.7). They concluded that this was possible if and only if the savings rate, s, equalled the population rate, n, multiplied by the capital requirement per unit of output, v, i.e. $s = vn$ (Bretschger, 1999; Solow, 2000; Thirlwall, 2002). Harrod (1939) denoted s, v and n as constants. If $s > vn$ then plans to increase the capital-output ratio will be less than plans to save and growth will drop away. By contrast, if $s < vn$ then plans to increase the capital-output ratio will exceed plans to save and

[222] In retrospect the imminent doom predicted by Malthus and Ricardo did not eventuate – primarily due to their underestimation of the influence of technology and substitution effects. Of course, Malthus and Ricardo are not alone in making this error – the highly popularised *Limits to Growth* study (Meadows *et al.*, 1972) also fell short in this respect. Unfortunately, this has led many economists to *assume* that backstop technologies will always exist to overcome neo-Malthusian predictions – this is despite binding physical constraints imposed by the laws of thermodynamics.

[223] The work of Ramsey (1928) on a mathematical theory of saving is considered by some commentators to be a key impetus behind Harrod's (1939) efforts – refer to Asimakopulos and Weldon (1965).

growth may run away.[224] Thus, economies appeared to be balanced on a 'knife-edge' (Bretschger, 1999; Thirlwall, 2002; Panico, 2003).

The major criticism of the Harrod-Domar model is that the predicted instability facing many economies never eventuated – in fact, empirical studies have shown that many western economies exhibit *near* steady state growth (Solow, 2000). This is because s, v and n are not simple constants as proposed by Harrod, but variables characterised by continuous change.[225] If it is assumed that changes to n result only in scale effects, it may then be argued that economic growth/decline is a result of either: (1) changes to the savings rate, s, or, (2) changes to the capital-output ratio, v. In a debate that would last many years, arguably without resolution, Keynesian economists such as Nicholas Kaldor[226], Joan Robinson, Richard Kahn and Luigi Pasinetti argued in favour of the savings rate, while neo-classical economists such as Robert Solow, Paul Samuelson and Franco Modigliani supported the capital-output ratio (Solow, 1988, 2000; Bretschger, 1999; Thirlwall, 2002). Given its dominant and widespread use today, the remainder of this Section focuses on the neo-classical growth model.[227]

10.2.2 The Solow Model

In 1956, Robert Solow published *A Contribution to the Theory of Economic Growth* – this was to become a landmark paper on economic growth (Jones, 1998, 2002). For this work, and subsequent contributions to the understanding of economic growth, he was awarded the economics Nobel Prize in 1987. Solow's models focused on the importance of technology rather than the savings rate as the key determinant of economic growth. Solow (1956) and

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[224] This condition, together with the preceding one, represents the so-called 'Harrod instability problem' (Solow, 2000; Thirlwall, 2002).

[225] The Harrod-Domar model assumes that s, v and n exist independently of each other i.e. possible dynamic feedbacks are overlooked. This criticism also applies to the neo-classical models that are shortly described.

[226] Nicholas Kaldor, a prominent Keynesian economist, has argued that it is difficult to understand economic growth without taking a sectoral approach (Kaldor, 1961; Thirlwall 2002; Panico, 2003). He emphasises the unique role played by manufacturing industries in generating economic growth through increasing returns, but also acknowledges that this growth can only occur through the physical transformation of raw materials, typically provided by farming and mining industries with diminishing returns to scale. Kaldor (1961) argues that agriculture provides the initial impetus for economic growth in industry. A fine balance ensures that industrial growth is neither supply-constrained due to agricultural prices being too high relative to industrial prices, or demand-constrained because they are too low. It is argued that through time the importance of agriculture as a market for industry products will decline in favour of export based markets.

[227] Developments in growth theory are not solely limited to the contributions of Keynesian and neo-classical economists. Other theories have also been developed. Nelson and Winter (1982) have, for example, developed an 'evolutionary economics' model of economic growth (Simmie, 2001; Loeschel, 2002). Of course, a comprehensive review of all contributions made in economic growth theory would be a monumental task – well beyond the scope of this thesis. Readers are instead referred to publications such as Aghion and Howitt (1998), Solow (2000), Foster and Metcalfe (2001), Salvadori (2003), Helpman (2004), and Aghion and Griffith (2005).

Swan (1956) were also the first to emphasise long run economic growth (Panico, 2003). Solow's models are built on two equations: (1) a production function, and (2) a capital accumulation equation.

The production function, presented in Equation 10.1, is of a Cobb-Douglas[228] form,

$$Y = K^{\alpha} L^{1-\alpha}, \tag{10.1}$$

where capital (e.g. tools, machinery and factories), K, and labour, L, combine to produce output, Y. It is assumed that the elasticities of output with respect to capital, α, and with respect to labour, $1-\alpha$, exhibit constant returns to scale (if factor inputs double then output will also double) i.e. $\alpha + (1-\alpha) = 1$. The production function of Equation 10.1 is typically rewritten in terms of output per worker (i.e. as a measure of labour productivity), $y = \frac{Y}{L}$, and capital per worker (i.e. as a measure of capital productivity), $k = \frac{K}{L}$, i.e.,

$$y = k^{\alpha}. \tag{10.2}$$

Given more capital a worker will therefore produce more output. But there are diminishing returns to capital per worker i.e. each additional unit of capital given to a worker increases the output of that worker by less and less (Solow, 1956, 1957, 2000; Jones, 1998, 2002; Helpman, 2004).

Capital accumulation is the focus of the second equation of the Solow model,

$$\dot{K} = sY - dK, \tag{10.3}$$

where the change in the capital stock over time, $\dot{K}$, equates to gross investment, sY, less depreciation, dK.[229] It is assumed that workers save a constant fraction, s, of their income[230]

[228] Cobb and Douglas (1928) proposed this production function while undertaking an analysis of US manufacturing (Thirlwall, 2002). They found that a value of ¼ for α mirrored empirical findings – without taking into account technological progress.

[229] 'Dot' notation is used to denote a derivative with respect to time i.e. $\dot{K} \equiv \frac{dK}{dt}$.

and that this saving is completely invested within the economy to accumulate capital[231]. Workers rent this capital to firms for use in production. It is further assumed that the capital stock depreciates by a constant fraction, d, every period.[232] Neo-classical economists typically rewrite the capital accumulation equation in terms of capital per worker,

$$\dot{k} = sy - (n+d)k, \qquad (10.4)$$

where the population growth rate, n, is assumed to be a constant.[233,234] This equation tells us that the change in capital per worker is a function of three terms: (1) investment per worker, sy, increases k; (2) depreciation per worker, dk, reduces k; and (3) the population growth rate, n, also reduces k.

To study economic growth neo-classical economists track how output per worker changes over time. A so-called 'Solow' diagram is often used for this purpose (Jones, 1998, 2002; Thirlwall, 2002). The Solow diagram depicted in Figure 10.1 consists of two curves drawn as functions of the capital-labour ratio, k: (1) investment per worker, sy, and (2) the amount of new investment required to keep capital per worker constant, $(n+d)k$ (Jones, 1998, 2002). The transformation in capital per worker over time may be described using the difference between the curves. If $sy > (n+d)k$, as at point k_0, then the economy is increasing its capital per worker or 'capital deepening'.[235] This continues until the amount of capital per worker remains constant i.e. $k = k_*$. Economists label this point the steady state.

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[230] Workers earn income from wages and salaries, w, and rental income from capital investments, r, such that across the entire economy $Y = wL + rK$. The goal of firms is to profit maximise output, Y, after making payments for both labour, wL, and rents for capital, rK.

[231] It is assumed here that the economy is closed i.e. the economy does not trade with other economies.

[232] Most neo-classical growth models assign d a value of between 0.05 and 0.10 (Jones, 1998, 2002).

[233] Two mathematical steps are required to rewrite the capital accumulation equation in terms of capital per worker: (1) economists 'take the logs and then derivatives' of the capital per worker equation, and then (2) combine this result with the capital accumulation equation. For full details refer to Jones (1998, p. 23 and p. 168).

[234] The population growth rate is used as a proxy for the labour force growth rate – it is also assumed that the labour force participation rate remains constant over time.

[235] If k_0 was positioned to the right of k (i.e. $sy < (n+d)k$) then investment per worker would be less than the amount required to keep capital per worker constant. This situation is known as 'capital widening'.

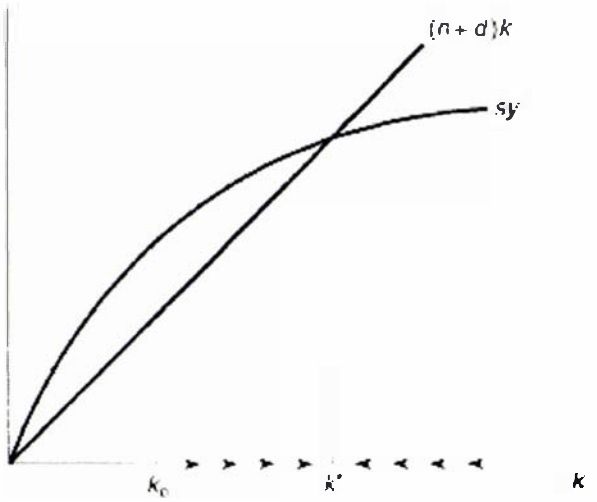

Figure 10.1 **The Solow Diagram.** Source: Jones (1998, p.25)

Careful consideration of this diagram reveals several key findings on economic growth. Firstly, an increase in the investment rate will only raise capital per worker temporarily. The economy will however be richer. Secondly, an increase in the population growth (or capital depreciation) rate will only temporarily lower capital per worker, but the economy as a whole will be poorer. Finally, a corollary of the preceding two findings, as currently formulated, is that it is impossible to derive continuous per worker growth in the model – a consequence of the diminishing returns exhibited by the individual factors of production. In other words, an economy may grow for a while, but not forever (Jones, 1998, 2002). Neo-classical economists argue that ongoing growth may only be achieved through technological progress.

10.2.3 The Solow Model with Technology

Technological progress is introduced into the Solow model to offset the diminishing returns to capital accumulation i.e. enabling labour productivity (output per worker) to grow *ad infinitum.* Through technology the amount of output generated from a given set of factor inputs may be increased. It is argued therefore that the long term growth rate of the economy is thus equal to the rate of technological progress. To account for technological progress a technology variable, A, is added to the production function of Equation 10.1[236,237]:

$$Y = K^{\alpha}(AL)^{1-\alpha}. \qquad (10.5)$$

[236] The technology variable added in this way is known as 'labour-augmenting'. Other possibilities include: 'capital-augmenting' (i.e. $Y = (AK)^{\alpha} L^{1-\alpha}$) and 'Solow-neutral' (i.e. $Y = A(K^{\alpha} L^{1-\alpha})$).

[237] Representing technological change as a single variable is very rudimentary. Authors such as Perrings (1987) and O'Connor (1993) have rigorously defined technology using a matrix translating factor inputs into outputs across several industries.

Technological progress occurs when the technology variable, A, increases over time. It is here that the key assumption of the Solow model is revealed. Technological progress is considered to be an exogenously determined constant i.e. it is assumed to be independent of the functioning of the rest of the economy. Or, put alternatively, there are no feedbacks between economic activity and technological advancement. Of course, this has been hotly contested in the literature – in fact, attempts to endogenise technology into models of economic growth provided the impetus behind the emergence of so-called 'New Growth Theory' (refer to Section 10.3 below).

Incorporation of technological progress into the Solow model is undertaken as follows (for full mathematical details refer to Jones (1998, pp.32-35)). Firstly, we make the assumption that A is growing at a constant rate,

$$\frac{\dot{A}}{A} = g, \tag{10.6}$$

where g denotes the growth rate of technology. Secondly, since k is no longer constant in the long term due to the presence of technological change, we must define another variable to consider steady state conditions. Neo-classical economists typically select the ratio of capital per worker to technology (known as the 'capital technology' ratio), for this purpose i.e. $\tilde{k} = \frac{K}{AL}$. Finally, equivalents of Equations 10.2 and 10.4 must be generated as a consequence of using the capital technology ratio. The production function becomes,

$$\tilde{y} = \tilde{k}^{\alpha}, \tag{10.7}$$

where $\tilde{y} = \frac{Y}{AL}$. The variable $\tilde{y}$ is known as the 'output-technology' ratio. The updated capital accumulation equation becomes,

$$\dot{\tilde{k}} = s\tilde{y} - (n + g + d)\tilde{k}. \tag{10.8}$$

Once again the transition dynamics of, say, a change in investment pattern through capital injection, or of a policy change which results in positive net migration, may be traced using a Solow diagram. Of course, the effect on long run growth is the same as occurred in the Solow model without technology. Changes brought about by investment or policy may only temporarily increase the economic growth rate i.e. until a new steady state is reached. Investment and policy changes result only in level effects – a raising or lowering of the output per worker, but not in continued growth. In the long term, the economic growth rate of the economy in the Solow model with technology will approximate the rate of technological progress.

A Note on Growth Accounting

In 1957 Solow published *Technical Change and the Aggregate Production Function.*[238] Solow demonstrated an accounting exercise which disintegrated growth in output into capital based growth, labour based growth and growth attributable to technological change (Jones, 2002; Helpman, 2004). The rate of growth of output that is given to a particular input equals the input's share of GDP multiplied by the rate of growth of the input. In this way, the contribution of all inputs is the weighted average of the growth rates of the inputs, in which the weight of every input equals its share of GDP (Helpman, 2004). Since Solow (1957) the work has been refined by authors such as Jorgenson and Griliches (1967) and more recently, Young (1995) and Jorgenson and Yip (2001). Despite growth accounting being useful in decomposing growth, it unfortunately reveals little about the causes of growth.

10.3 Endogenous or New Growth Theory

Unlike the neo-classical growth models of Solow where the emphasis is on the mere effect of technological change (i.e. through the use of an exogenous variable), endogenous or 'new growth theory' attempts to understand how technological progress occurs (Grubb *et al.*, 1995; Jones, 1998, 2002; Thirlwall, 2002). Endogenous growth theory builds on the recognition that technological innovation is in its own right an economic activity – arising from the efforts of profit-maximising activities (Loeschel, 2002). Research on endogenous growth theory is very much in its infancy (Loeschel, 2002; Thirlwall, 2002). Notable contributions to date have included the work of Romer (1986, 1990), Lucas (1988), Grossman and Helpman (1991, 1994), Aghion and Howitt (1992) and Young (1993). The focus of these contributions has been on explaining technological change from four closely related perspectives[239]:

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[238] Abramovitz (1956) had previously alluded to the possibility of growth accounting. Nevertheless, it was Solow (1957) who provided the analytical framework for its operationalisation.
[239] Economists often label the flow-on effects of technology as a positive externality. An externality is a consequence of an activity that is not fully accounted for in a market (Bannock *et al.*, 1992).

- *Research and development.* Romer (1986, 1990) was among the first to suggest research and development as a key driver of technological change.[240] Robert Lucas (1988), another Nobel Prize winner, has focused on the effects of human capital formation through education.[241] Corporate investment in research and development is often in response to market conditions.
- *Spillovers.* Grossman and Helpman (1991, 1994) have concentrated on the technological spillovers from trade and investment. Spillovers occur when knowledge is created in one economic activity that may be of use, or indirectly (often without payment) leads to technological improvements, in other economic activities. Griliches (1992) has demonstrated the empirical significance of spillovers. Spillovers may occur within industries or between industries. At a regional level spillovers may occur within a region, between regions, and with other nations.
- *Creative destruction.* Faber *et al.* (1990) and Aghion and Howitt (1992) have generated models of economic growth based on Schumpeter's (1942) notion of 'creative destruction'. Schumpeter (1942) distinguishes three stages of the process of technological change (1) invention, (2) innovation – the transformation of the invention into a commercial product, and (3) diffusion – the process of gradual adoption of the innovation from niche market to widespread use.
- *Technology learning.* Young (1993) builds on the earlier work of Arrow (1962) on 'learning-by-doing'. Empirical studies have shown that the cost of producing a commodity decreases as a function of cumulative production i.e. we learn how to do things at less cost the more often we do it (Ryan, 1995; Loeschel, 2002; Castlenuovo *et al.* 2005). Technology learning, or learning-by-using, is a more recent derivative of learning-by-doing – it refers to worker uptake of new technologies through their use. Learning-by-doing occurs most often in the innovation phase of technological change, while learning-by-using occurs during the diffusion phase (Rosenberg, 1982).

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[240] Romer (1986) and Lucas (1988) are often credited with sparking the so-called 'first wave' of research into endogenous growth theory, while Romer (1990) is credited with initiating endogenous growth theory's 'second-wave'. The key difference between Romer's two papers, and between the first and second waves of endogenous growth theory, lies in the movement from explaining growth using knowledge accumulation in an aggregate macro economy, to explaining growth using the detailed micro mechanics of ideas through the interaction between a research sector, an intermediate capital manufacturing sector and a final goods producing sector. This weaving together of macro and micro economies is arguably the greatest contribution made by the new growth theorists.

[241] Uzawa (1965) had however previously developed a human capital driven model of productivity improvement.

10.3.1 The Romer Model

The essence of new growth theory is perhaps best captured by considering one of its principle models. The Romer (1990) model is selected here for two key reasons: (1) it is one of the first endogenous growth models to be developed; and (2) the model's salient features have appeared in many subsequent models. Beginning in the 1980s, Paul Romer, over a series of papers, formalised the relationship between the economics of ideas and the economics of growth (Romer, 1986; Jones, 1998, 2002; Helpman, 2004). A full account of these developments is provided in Romer's (1990) paper entitled *Endogenous Technological Change*.

Romer's (1990) endogenous growth theory is founded on two key observations. Firstly, ideas are inherently nonrivalrous i.e. once conceived anyone can apply them. By contrast, most economic commodities are rivalrous – the use of a commodity by one person prohibits its use by another. Secondly, ideas are at least partially excludable. A commodity is excludable if its owner can prevent others from using it. Excludable commodities allow their producers to capture the benefits they produce, while unexcludable commodities often have spillover benefits not captured by their producers.[242] Copyrights and patents are often used to control the degree of excludability of ideas.[243] Ideas are only partially excludable because they often create benefits that the owner cannot completely capture.

The nonrivalry and partial excludability of ideas necessitates that their transformation into commodities may only occur in an imperfect market with increasing returns to scale. This is because the incentive to create a new idea is typically dependent upon the inventor earning profits from it. The transformation from idea to commodity involves a fixed cost of production, but zero marginal costs. Of course, nonrivalrous ideas are typically embodied in manufactured rivalrous commodities for sale purposes – which are characterised by marginal costs. Nevertheless, the important point here is that an idea will generally be transformed into a commodity if the private benefits of a commodity exceed its one-time invention costs. This necessitates the presence of increasing returns to scale and imperfect markets.

[242] Commodities with positive spillovers tend to be underproduced by markets (government intervention is often required here to provide such commodities e.g. education, healthcare, infrastructure provision), while commodities with negative spillovers are often overproduced/utilised by markets (government intervention is required here to avoid the 'tragedy of the commons' problem).
[243] Douglass North (1981), another Nobel Prize laureate, noted that until the advent of robust property rights there had been little incentive for inventors to develop new methods of production or advanced consumer commodities. It can therefore be argued that an idea with a high social rate of return will not be transformed into a commodity unless legally protected private benefits exist.

In the Romer model technological progress is driven by the research and development process – in particular, the search for new ideas by researchers seeking profit from their inventions (Jones, 1998, 2000; Romer, 1990). The Romer model consists of two main elements: (1) a production function, and (2) a set of equations describing how factor inputs evolve over time.

Unlike the Solow model however, the aggregate production function describes how the stocks of capital, K, and labour devoted to producing economic output, L_y, combine to produce output based on a stock of ideas, A. The production function is modelled as:

$$Y = K^{\alpha}(AL_y)^{1-\alpha}. \tag{10.9}$$

The production function exhibits increasing returns to scale as a result of the inclusion of the stock of ideas, A. The increasing returns to scale are a consequence of the nonrivalrous nature of ideas (Jones, 1998, 2002).

The equations describing how capital and labour evolve over time are similar to those of the Solow model. Firstly, the capital accumulation equation,

$$\dot{K} = s_k Y - dk, \tag{10.10}$$

where s_k denotes a given savings rate. Secondly, the labour accumulation equation,

$$\frac{\dot{L}}{L} = n, \tag{10.11}$$

which assumes that labour grows at the exogenous population rate, n. The Romer model, unlike the Solow model, endogenises technological progress. To complete the model an equation is therefore required to describe how the stock of ideas, A, changes over time,

$$\dot{A} = \bar{\delta} L_a, \tag{10.12}$$

where L_a is the labour devoted to producing new ideas[244] and $\bar{\delta}$ is that rate at which new ideas are discovered. Of course, it is unlikely that $\bar{\delta}$ is constant. Careful consideration of how ideas

244 The total labour force, L, assuming full employment, equates to L_y plus L_a.

are discovered reveals that $\bar{\delta}$ is probably a function of the stock of ideas (Romer, 1990). If, for example, the pool of ideas in the past raises the productivity of current researchers then $\bar{\delta}$ would be an increasing function of A (Jones, 1998, 2002). Or alternatively, if the most obvious ideas are invented first and subsequent ideas are increasingly more difficult to discover then $\bar{\delta}$ would be a decreasing function of A (Jones, 1998, 2002). This line of thinking suggests,

$$\bar{\delta} = \delta A^{\phi}, \tag{10.13}$$

where ϕ and δ are constants. The term ϕ indicates the productivity of the research i.e. if $\phi > 1$ then the productivity of researchers is an increasing function of A – a positive knowledge spillover exists[245]; if $\phi < 1$ then the productivity of researchers is a decreasing function of A – the discovery of new ideas becomes harder over time.[246]

Romer (1990) also points out that the productivity of researchers may also depend on the number of people engaged in idea discovery. Duplication of ideas, for example, may occur with increasing numbers of researchers. Or, alternatively, the formation of research teams may accelerate the creation of ideas. To this end, Romer (1990) modifies L_a to include a parameter, λ, for idea creativity – where λ is a constant between 0 and 1. We may now combine $L_a{}^{\lambda}$ with Equations 10.12 and 10.13 to obtain:

$$\dot{A} = \delta L_a{}^{\lambda} A^{\phi}. \tag{10.14}$$

Equation 10.14 completes the Romer model. The key feature of this equation, and of the Romer model, is the feedback loop between the change in the stock of ideas over time and the stock of ideas itself. It is this feature that endogenises technological change within the model. Overall, the long run growth rate in the Romer model is determined by Equation 10.14, which in itself is ultimately a function of population growth rate – in order to generate growth the number of ideas must be expanding over time, which can only occur with population growth.[247] Changes

[245] In reference to Isaac Newton's famous statement, "If I have seen farther than others, it is because I was standing on the shoulders of giants", Jones (1998, p.93) refers to this positive knowledge spillover as the "standing on the shoulders of giants" effect.

[246] If $\phi = 1$ then the positive knowledge spillovers exactly offset the increase in difficulty of discovering new ideas.

[247] If the productivity of research is proportional to the existing stock of ideas the long-run growth may be sustained. Under this situation the productivity of research grows over time despite the number of

in the investment rate or policy initiatives aimed at subsidising research, as with the Solow model, result only in level effects i.e. growth occurs along a transition path until a new steady state is reached.

It should be noted that during the mid-to-late 1960s economists such as Uzawa (1965), Phelps (1966), Shell (1967) and Nordhaus (1969) developed similar growth models. The distinguishing feature of Romer's (1990) contribution was to explain how technological progress could be modelled through a path involving the creation of new designs, the legal patent of these designs, sale of the designs to manufacturers, production by manufacturers, and ultimately final consumption. Navigating this path was according to Jones (1998, 2002) only possible however once economists such as Spence (1976) and Dixit and Stiglitz (1977) better understood the microeconomic basis for imperfect competition in a general equilibrium setting.

10.3.2 Other Endogenous Growth Models

Several other endogenous growth models have also been developed. It is beyond the scope of this thesis to investigate all such models. Nevertheless, two further commonly cited endogenous growth theory models require mention. First, the so-called 'AK' model. In this model the production function for output generation takes the following form,

$$Y = AK \,, \tag{10.15}$$

where A is some positive constant i.e. $\alpha = 1$. Under this model Y is linear in K – the key property of the AK model. If we assume that capital accumulates as per Equation 10.4 then the growth rate of the economy under the AK model will be an increasing function of the investment rate. Policies that increase the investment rate will therefore increase the growth rate of the economy. Of course, this is the case where the transition dynamics never end. Unfortunately, no theoretical basis can be given for setting α to 1. Moreover, empirical studies certainly do not corroborate a linear model.

The second model, created by Robert E. Lucas Jr (the 1995 Nobel laureate in economics), is based on human capital. The Lucas (1988) model assumes a production function very similar to Equation 10.1,

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researchers being constant. This improbable case produces a model similar to the AK model described below – it is also characterised by similar limitations.

$$Y = K^{\alpha}(hL)^{1-\alpha}, \tag{10.16}$$

where h is a measure of 'human capital' per worker. Human capital evolves over time according to the following differential equation,

$$\dot{h} = (1-u)h, \tag{10.17}$$

where u is time spent working, and $1-u$ is time spent accumulating skills. Growth in human capital is therefore a function of time invested in generating skills. By corollary, economic growth must thus also be a function of time invested in generating skills. The effect of policy changes or interventions on growth in the Lucas (1988) model will be as per the Solow model with technology – as a consequence of the labour-augmenting nature of technology/human capital.

The Romer (1990) model, and AK and Lucas (1988) models, typify the two main pathways that neo-classical economists have pursued in endogenous growth theory. On the one hand, the Romer-like models have generated increasing returns through imperfect competition brought about by the intentional efforts of inventors seeking profits. On the other hand, the AK- and Lucas-like models have generated increasing returns by maintaining perfect competition and accumulating knowledge by some by-product of the economy such as human capital formation.

10.4 Critique of Growth Theories as Applied to Environmental and Regional Models

The neo-classical growth models presented above have several shortcomings, over and above those already alluded to. These shortcomings may lead to system instabilities, including delayed feedbacks which may result in irreversible change. These shortcomings include:

- *Cobb-Douglas production functions*. Authors such as Benhaim and Schembri (1994), Victor (1991), Ayres (2001), and Ayres and van den Bergh (2005) *inter alia* have identified several shortcomings with using Cobb-Douglas production functions. Victor (1991, p.196), for example, states that "the potential for additional substitution never diminishes" in a Cobb-Douglas production function. Ayres (2001) and Ayres and van den Bergh (2005) argue that many economists have overlooked the critical role played by minor factor inputs in the Cobb-Douglas production function – in particular, the commodities (and their physical characteristics i.e. embodied mass and energy) used in intermediate consumption.

- *Only one homogeneous output*. Many neo-classical growth models assume that only a single homogeneous output is produced by the economy. Such models make no allowance for unique characteristics of the different commodities produced within the economy.
- *Unique role of manufacturing industries*. The unique role played by manufacturing industries in an economy, in particular the creation of capital, is largely ignored.
- *Path dependence, uncertainty, discontinuity and heterogeneity of investment decisions*. Weyant and Olavson (1999) note that aggregative models ignore path dependence (e.g. the need to process intermediate goods and delays in capital formation), uncertainty in major innovations, discontinuity in the process of technological change, and the heterogeneity of firm behaviour and investment decisions.
- *No international or interregional trade*. Another major limitation is that the role played by trade is often ignored. Thirwall (2002) suggests that this is also a factor of the very supply (production) orientated nature of the neo-classical models. Little credence is given to an economy's balance of payments, in particular the demand for exports elsewhere.
- *The process of technological change*. Consideration of how the key determinants of technological change are interconnected, respond in relation to one another, respond in relation to influences within the wider economic system, whether multiple trajectories or pathways exist – such queries indicate that theory underpinning the process of technological change is still very much in its infancy (Bretschger, 2005). Quantifying the impacts, for example, of price induced technological change poses a major theoretical problem.
- *Convergence*. A principle focus of growth theory has been on the convergence between rich and poor countries (Jones, 1998, 2002; Ayres, 2001; Ayres and van den Bergh, 2005). Much of the growth theory literature has been developed with the intention of investigating solely this issue. Growth models, like other models, are context sensitive – thus, taking a growth model designed to reveal insights on the convergence debate, and in turn, expecting it to explain environmental issues, may be entirely inappropriate.
- *Nation focus*. The vast majority of growth models have been constructed at the national level. There are however significant differences between national and regional economies e.g. the existence of interregional trade, the greater openness of the economy, and ease of labour force exchange. Many of the working assumptions of neo-classical growth theory could never be justified in a world which recognises space (Richardson, 1973). Space is incompatible with a single industry aggregative economy, perfect competition, complete certainty, marginal adjustments in prices, evenness in the

spread of technologies, zero transportation costs and other lesser conditions of neo-classical economics (Richardson, 1973).

- *Biophysical constraints.* A significant weakness of neo-classical growth theory is the myopic focus on technological change as the key determinant of long term growth. Growth theory pays little respect to well-known biophysical constraints. Many growth theorists and economists (e.g. Barnett and Morse (1963), Simon (1981) and Romer (1990)), for example, assume that new ideas or designs will offset any diminishing returns resulting from resource scarcity *etc*., but to be useful such designs must take on a physical form constrained by, at least, the laws of thermodynamics.[248] Although technological change has to date offset diminishing returns from resource scarcity *etc*., it is highly uncertain whether this trend will continue, particularly in the long term (Faber *et al.* 1990; Kaufman, 1995; Ryan, 1995; Ayres, 2001; Ayres and van der Bergh, 2005; Bretschger, 2005; Vollebergh and Kemfert, 2005)

10.5 Natural Resources and Economic Growth

In this Section theoretical growth models are developed that incorporate the depletion and degradation of natural resources. The model builds on the neo-classical models described earlier in this Chapter, but incorporates features that address some, but not all of the biophysical constraints identified in the previous Section. At the core of the model is a race between the increasing returns to scale induced through technological change and possibilities of substitution, and diminishing returns to scale resulting from resource scarcity and environmental degradation (e.g. pollution). Samuelson and Nordhaus (1989, p. 859) note that, "In the race between diminishing returns and advancing technology, technology has [to date] won by several lengths".[249] Nordhaus (1992, p.2) however warns that, " ... to dimiss today's ecological concerns out of hand would be reckless. Because boys have mistakenly cried 'wolf' in the past does not mean that the woods are safe." Authors like Faber *et al.* (1990), Kaufman (1995), Ryan (1995), and Ayres (1995, 2002) also support this argument.

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[248] Authors such as Chapman and Roberts (1983) and Ruth and Cleveland (1994) argue that the laws of thermodynamics play a critical role in understanding the longer term consequences of technological change. They show that as metals become harder to extract, the amount and cost of energy required increases – thus becoming a key determinant in economic growth (Ryan, 1995).

[249] Jones (2002) has analysed the factor share of energy in the U.S. economy for the period 1949-1999. He concludes that " ... the energy share shows a general decline, apart from the sharp spike associated with the oil-price shocks of the 1970s" (Jones, 2002, p.184). He attributes this decline to new discoveries of fossil fuels and to new ways of tapping into reserves previously considered inaccessible. Because the energy factor share is declining he argues that the use of a Cobb-Douglas production function to model natural resource depletion may be inappropriate; instead he favours the use of a constant elasticity of substitution (CES) production function. Time constraints imposed on the completion of this thesis prohibited exploration of this alternative.

For ease of mathematical presentation the model developed below treats the economy as an aggregated whole i.e. it is assumed that the economy produces only one homogeneous output. A further simplification is that the economy is assumed to be dependent upon only a single resource.

10.5.1 Modelling the Implications of Land Use

Jones (2002) has modified the Solow model with technology to include land. He assumes that only a fixed amount of land, T, is available in each time period; with output generated according to the following production function,

$$Y = AK^{\alpha}T^{\beta}L^{1-\alpha-\beta}. \tag{10.18}$$

This function exhibits diminishing returns to capital and labour i.e. as the economy expands it gets less productive at the margin. This impact may however be offset by increasing returns to all inputs brought about by technological change, A. By reformulating the model in endogenous terms the implications of population growth could be studied more fully i.e. the trade off between having more people to create ideas, and increasingly less space to support each person.[250]

10.5.2 Modelling of the Depletion of a Non-Renewable Resource

Unlike land, which is assumed to be in fixed supply, non-renewable resources such as coal, fossil fuels, minerals and the like represent finite resources that may over time be entirely depleted. The depletion of a non-renewable resource may be included in the model as follows,

$$Y = AK^{\alpha}E^{\beta}L^{1-\alpha-\beta} \tag{10.19}$$

where once again A augments the entire production function, and E represents depletion of the non-renewable resource. The behaviour of the non-renewable resource stock, R, over time may be described by the following differential equation,

$$\dot{R} = -E. \tag{10.20}$$

[250] Simon (1981) is a very strong advocate of the 'more people, more ideas' position. Others are skeptical, for example, Dasgupta and Heal (1979, p.194) question this position, "... if only for reasons of space".

If we assume that a constant fraction of the non-renewable stock is depleted during each period[251], i.e. $s = \frac{E}{R}$, then the behaviour of the stock over time may be described in further detail by the following differential equation.

$$\frac{\dot{R}}{R} = -s, \qquad (10.21)$$

Based on Equation 10.21 it can be mathematically shown that the non-renewable stock, R, exhibits negative exponential growth at the rate, s, over time Under this model an increase in the depletion rate, s, will reduce the long-term growth rate of the economy i.e. the non-renewable resource is used up faster, leaving less of the resource for production of future output. Or, put alternatively, by reducing the current depletion rate, s, it is therefore possible to increase the long-term growth rate of the economy. Of course, this impact may be offset by the increasing returns that may be generated through technological change or via substitution between factor inputs.

The key finding of the preceding two Sections is that the presence of natural resources (including land) reduces the long run growth rate of the economy. The production functions exhibit diminishing, rather than constant returns to capital and labour. These diminishing returns are the result of: (1) population pressure on finite resources reduces growth in proportion to the population growth rate, and (2) the depletion of non-renewable resources slows growth in proportion to the share of these resources in production (Jones, 2002). Nevertheless, these impacts may be offset through technological change or via substitution between factor inputs. However, this offset, as pointed out by Ryan (1995), is constrained by the laws of thermodynamics. It is therefore impossible to know if technological change will continue in the future to compensate for the diminishing returns brought on from depleting fixed or finite resources.

[251] Economists typically use prices to describe the depletion variable, E. A standard result from such analyses is that in the long run, a constant fraction of the remaining stock of resource is depleted in each time period (Jones, 2002).

Chapter Eleven

Auckland Region Dynamic Ecological-Economic Model

In this Chapter a system dynamics model of Auckland Region's environment-economy interactions is developed. The model, known as the Auckland Region Dynamic Environment-Economy Model (ARDEEM), builds on the static monetary and physical flow models developed in Chapters 4, 5 and 6 and the (theoretical) models of economic growth discussed in Chapter 10. The model is characterised by positive and negative non-linear feedbacks between its component modules. The purpose of the model is not to predict Auckland Region's economic future, but instead to highlight possible physical and economic consequences under various scenarios. A key reason for the adoption of a system dynamics modelling framework is that it allows a great deal of flexibility in setting the scenarios that may be investigated. The scenarios themselves are designed to capture not only the 'business as usual' situation, but also the dynamic physical and economic consequences resulting from more extreme change. The ARDEEM system dynamics model is presented in Vensim® DSS format in the Chapter 11 directory of the accompanying CD-ROM. The directory also contains a full program listing for the ARDEEM model – labelled ARDEEM.txt.

11.1 Structure of ARDEEM

ARDEEM is a novel system dynamics model designed to simulate the combined environmental and economic implications of change in the Auckland Region between 1998 and 2051. The focus of ARDEEM is therefore on the medium to long term (i.e. 30 to 70 years) consequences of change in the Auckland Region. ARDEEM cannot therefore be expected to capture short term fluctuations in economic activity such as those arising from cyclical commodity price fluctuations.[252] The ARDEEM model consists of the following integrated modules:

- *Population module*. This module simulates population growth by age-sex cohort. The population module provides inputs directly for the labour force, economic flow and physical flow modules, and indirectly for the growth module. It is also used in the generation of several key indicators, including resource use per capita, GRP per capita and so on.

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[252] Other modelling frameworks such as Computable General Equilibrium (CGE), optimisation models (e.g. MARKAL), and some econometric models are better suited for this purpose.

- *Labour force module.* This module takes outputs from the population module by age-sex cohort and generates estimates of total labour force, employment and unemployment by industry.
- *Growth module.* This module generates estimates of economic output by industry. The cornerstone of the growth module is a production function with constant returns to scale. The production function has the following factor inputs: employment (as generated by the labour force module), commodity imports and use (from the economic flow module), and manufactured capital stocks. The production function is augmented with indices representing technological change and natural capital depletion/degradation. The output estimates generated by this module feed into the economic flow and economic physical flow modules.
- *Economic flow module.* This module describes the financial flow of commodities within the Auckland Region economy. This includes commodity supply, use, imports and exports. The module provides inputs for the growth and economic physical flow modules and generates key economic aggregates including value added (regional GRP), balance of trade, labour productivity, capital productivity and so on.
- *Economic physical flow module.* This module describes the Auckland Region economy in physical (mass) flow terms, including commodity supply, use, imports and exports, and is closely related to the economic flow module. The focus of the module is on the within economy physical flows. Monetary estimates of commodity supply and use from the economic flow module are converted into physical equivalents based on price ($ per tonne) and indices of improvements in eco-efficiency.
- *Environment-economy physical flow module.* This module describes the physical flow of raw materials and residuals associated with economic activity in the Auckland Region. The focal point of this module is the physical flow of ecological commodities not conventionally measured in economic markets. The module draws on the output by industry estimates of the growth module, exogenous estimates of raw material use/residual generation per $ output, and indices of improvements in eco-efficiency to generate its estimates of the physical flow of raw materials and residuals.

The linkages between the various modules are described in Figure 11.1. Sections 11.3 to 11.8 fully describe ARDEEM. Verification and validation of the model is conducted in Section 11.9. In Section 11.10 three scenarios are developed and simulated: (1) 'business as usual', (2) 'cornucopian growth', and (3) 'prudent pessimism'. The final Section of this Chapter outlines the major limitations of ARDEEM model including the identification of key areas for future development.

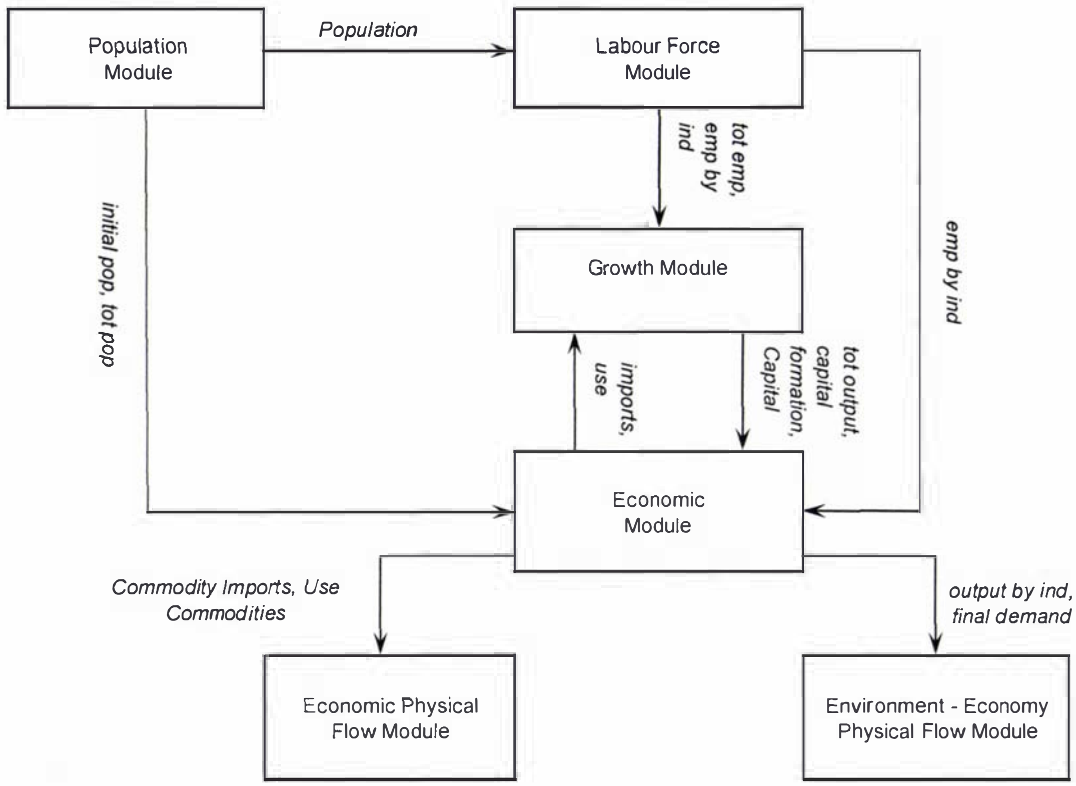

Figure 11.1 **ARDEEM Module Linkages**. Note: The italicised key variables pass information between the modules.

11.2 Brief Description of ARDEEM's Mathematical Nomenclature

This Section provides a brief description of ARDEEM's mathematical nomenclature and naming conventions. Specifically, this includes:

- *Upper case stocks*. All stocks begin with a capital letter.
- *Lower case flows and converters*. All flows and converters begin with a lower case letter.
- *Subscripted arrays*. Variables with multiple dimensions are arrayed. A population stock, for example, may have two dimensions, namely: age and sex. In ARDEEM variables with arrayed dimensions are denoted by variable names with suffix subscripts. Vensim's® array functionality substantially reduces (1) the visual clutter of influence diagrams, and (2) the time required to program equations.
- *Full variable names*. To aid in the comprehension of Vensim® system dynamics influence diagrams and mathematical formulae, variables names are presented in full.

A complete list of ARDEEM arrays and their elements is presented below:

a	= 0 to 4 yrs, 5 to 9 yrs, 10 to 14 yrs, 15 to 19 yrs, 20 to 24 yrs, 25 to 29 yrs, 30 to 34 yrs, 35 to 39 yrs, 40 to 44 yrs, 45 to 49 yrs, 50 to 54 yrs, 55 to 59 yrs, 60 to 64 yrs, 65 to 69 yrs, 70 to 74 yrs, 75 to 79 yrs, 80 yrs and over
c	= Com01, Com02, Com03
f	= HhldCons, OFD, IntRegExp, IntNatExp
i	= Ind01, Ind02, Ind03
imp	= Interregional, International
p	= 0 to 9 yrs, 10 to 19 yrs, 20 to 29 yrs, 30 to 39 yrs, 40 to 49 yrs, 50 to 59 yrs, 60 to 69 yrs, 70 to 79 yrs, 80+ yrs
s	= male, female
rm	= Rm01, Rm02, Rm03, Rm04, Rm05
r	= Res01, Res02, Res03, Res04, Res05, Res06

11.3 Population Module

In this Section, a population module is developed that disaggregates Auckland Region's population by sex and five year age cohorts (i.e. 0 to 4 years, 5 to 9 years ... 75 to 79 years, and 80 years and over). Sub-national population projections from Statistics New Zealand (2004) suggest that Auckland Region will grow from a 2001 base population of 1,216,900 to between 1,624,400 (low projection series) and 1,926,500 (high projection series) by 2026. This represents total population growth of between 33.5 percent (low) and 58.3 percent (high) over the 25 year period. Over two-thirds of New Zealand's total population growth between 2001 and 2026 is projected to be in the Auckland Region (Statistics New Zealand, 2004). By 2026 Auckland Region is projected to be home to more than 37 percent of New Zealand's total usually resident population, compared with 31 percent as at the 2001 Census. The implications of this growth cannot be understated:

- *Changes in the types of infrastructure required.* Although Aucklanders are relatively young, when compared with other New Zealanders, the average age has been steadily rising (Statistics New Zealand, 1998). Changes in the age structure of Aucklanders could potentially affect birth rates, housing requirements, health and education requirements, consumption patterns, and the nature of the labour force.
- *Pressure on existing infrastructure.* Much of Auckland Region's infrastructure is at capacity or the end of its life, or needs to meet higher environmental standards (Auckland Regional Council, 1999). Of particular concern is the pressure being placed

on transportation networks, water supply services, wastewater treatment, and energy generation infrastructure.[253]

- *Demand for new infrastructure.* This includes demands for power stations, transportation networks[254], social and community services (i.e. hospitals, schools, libraries, museums, recreational facilities), open space (i.e. neighbourhood reserves, parklands and sports grounds) and additional housing[255,256].
- *Structural mix of the economy.* Community, social and personal services play a more significant role in the Auckland Region economy than elsewhere in New Zealand. It can be argued that this role may be exacerbated through growth in population based services such as health and education. Export education, for example, has over recent years become a substantial industry in the Auckland Region economy.

The ARDEEM population module is shown as a Vensim® system dynamics influence diagram in Figure 11.2. Note how the age-sex cohort structure of the model is captured using Vensim's®array functionality, rather than by building multiple population stocks with inflows and outflows for each age-sex cohort.

[253] The pressure of population growth on Auckland Region's infrastructure may arguably be seen through a number of local crises and associated policy responses including: the 1994 energy blackouts (resulting from a poorly maintained and ageing energy supply network), 1998 water shortage (resulting in the construction of the so-called 'Waikato pipeline'), and ongoing traffic congestion (leading to substantial local and central government expenditure on roading projects).

[254] Household trends in car ownership and energy consumption during the 1990s have exacerbated these demands by growing at rates substantially higher than the population growth rate (Auckland Regional Council, 1999).

[255] The average home occupancy rate in Auckland Region has been steadily rising (Statistics New Zealand, 1998; Auckland Region Council, 1999) Although this trend may to some extent dampen the demand for additional housing, it is insufficient to offset the likelihood of substantial future housing requirements. By contrast, the New Zealand home occupancy rate has been steadily declining.

[256] Over the last two decades Auckland Region territorial local authorities, supported by the Auckland Regional Council, have through initiatives such as the Auckland Regional Growth Forum advocated a more compact urban form, resulting in greater numbers of apartments, terraced housing and infill housing. Although trends for traditional housing have persisted, there has been a significant increase in higher density living.

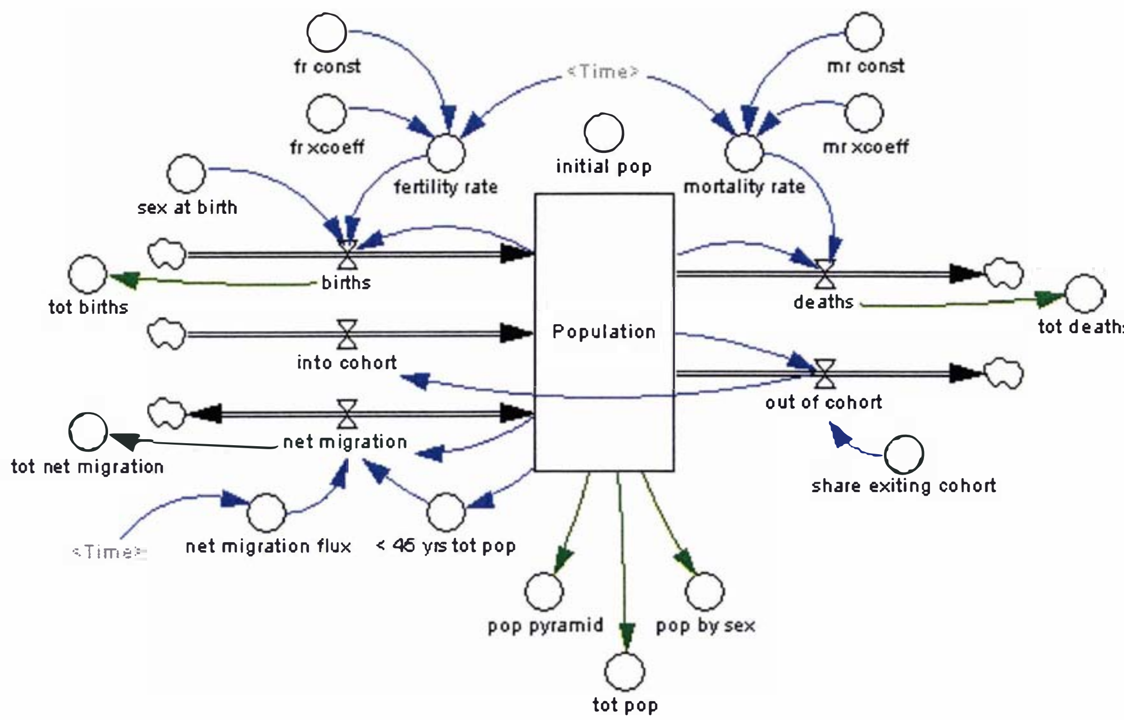

Figure 11.2 Population Module Influence Diagram

The population module may be described using the following mathematical equations[257]:

Stocks

$Population_{a,s}(t + dt)$	$= Population_{a,s}(t) + (births_{a,s} + net\ migration_{a,s} + into\ cohort_{a,s} - deaths_{a,s} - out\ of\ cohort_{a,s}) \times dt$. As measured in number of people.
where:	
Initial $Population_{a,s}$	$= initial\ pop_{a,s}$ for the 1998 base year (no. people).

<u>Inflows</u>

$births_{a,s}$	$= \sum_{a,s}((Population_{a,s}(t) \times fertility\ rate_{a,s} / 1000) \times sex\ at\ birth_s)$ [258] As measured in number of people.

[257] It is important to note that variables are defined only once, at first use, to avoid unnecessary duplication.

[258] Double summations, such as $\sum_{a=0}^{n} \sum_{s=f,m} (Population_{a,s}(t))$, are summarised here as $\sum_{a,s}(Population_{a,s}(t))$.

where:

fertility rate$_{a,s}$	= (*fr xcoeff*$_{a,s}$ × LN((t) – 1971)) + *fr const*$_{a,s}$
fr const$_{a,s}$	= the constant of a logarithmic time series regression equation describing the Auckland Region fertility rate of a particular age-sex cohort between 1971 and 2000.[259] If s = male then *fr xcoeff*$_{a,s}$ is set to zero. Similarly, *fr xcoeff*$_{a,s}$ for females aged under 10, and over 50, years of age is set to zero.
fr xcoeff$_{a,s}$	= the 'x' coefficient of a logarithmic time series regression equation describing the Auckland Region fertility rate of a particular age-sex cohort between 1971 and 2000. Once again, if s = male, or s = female and a < 10 or a >= 50 years, then *fr const*$_{a,s}$ is set to zero.
sex at birth$_s$	= shares of sex at birth. It is assumed that likelihood of a male or female being born is the same.

net migration$_{a,s}$	= *net migration flux* × (*Population*$_{a,s}$(t) / < *45 yrs tot pop*)

where:

net migration flux	= a graph showing annual net migration into/from Auckland Region. These estimates are taken directly from Statistics New Zealand's (2004) sub-national population projections (medium series).
<45 yrs tot pop	$= \sum_{a=0}^{45} \sum_{s=f,m} (Population_{a,s}(t))$. Total population under 45 years of age.

into cohort$_{a,s}$	= *out of cohort*$_{a,s}$. If a represents the 5 to 9 age cohort then it is assumed that one fifth of the 0 to 4 age cohort moves into the 5 to 9 age cohort each year. A similar pattern applies to other age cohorts. As measured in number of people.

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[259] Linear and logarithmic time series regressions are utilised throughout this Chapter to account for the changing nature of exogenous variables. The pros and cons of using time series regression in this way is given at the end of Section 11.3. The use of regression equations is easily identified according to the 'xcoeff' and 'const' endings of variable names. Appendix M provides full details of all variables determined using time series regression. For each time series regression this includes: the type of regression (i.e. linear or logarithmic), time series period (e.g. from 1971 to 2000), the regression equation, R-squared value, and data source. In most cases the p-values, F-ratios and Durban-Watson statistics of the regression equations were found to be acceptable. All regression equations were 'sense' checked by graph equations against observed data; with slope, direction and residual outliers being investigated.

Outflows

deaths$_{a,s}$	= *Population*$_{a,s}$(*t*) × (*mortality rate*$_{a,s}$ / 1000). As measured in number of people.
where:	
mortality rate$_{a,s}$	= (*mr xcoeff*$_{a,s}$ × LN((*t*) – 1971)) + *mr const*$_{a,s}$
mr const$_{a,s}$	= the constant of a linear or logarithmic time series regression equation describing the mortality rate of a particular age-sex cohort between 1971 and 1995.
mr xcoeff$_{a,s}$	= the 'x' coefficient of a linear or logarithmic time series regression equation describing the mortality rate of a particular age-sex cohort between 1971 and 1995.
out of cohort$_{a,s}$	= *Population*$_{a,s}$(*t*) × *share exiting cohort*. As measured in number of people.
where:	
share exiting cohort	= the share of population in each age-sex cohort exiting the cohort in each full time step. It is assumed that the number of people in each year of age in a cohort is the same i.e. one fifth of the age cohort moves into the next cohort each year.

Reporting variables

pop by sex$_s$	= $\sum_{a=0}^{n}(Population_{a,s}(t))$. Total population by sex (no. of people).
tot births	= $\sum_{a,s}(births_{a,s})$. Total births (no. of people).
tot deaths	= $\sum_{a,s}(deaths_{a,s})$. Total deaths (no. of people).
tot net migration	= $\sum_{a,s}(net\ migration_{a,s}))$. Total net migration (no. of people).
tot pop	= $\sum_{a,s}(Population_{a,s}(t))$. Total population (no. of people).
pop pyramid$_{0\ to\ 9,s}$	= $Population_{0\ to\ 4,s} + Population_{5\ to\ 9,s}$. Total population for the 0 to 9 age cohort by sex for reporting in a population pyramid. Other population pyramid age-sex cohorts were calculated in an analogous manner (no. of people).

The reliance on time series regression to determine fertility and mortality rates represents an attempt to use statistical techniques to capture trends in these rates over the last thirty years. Modellers such as Boumans *et al.* (2002), Jollands *et al.* (2005) and Ruth *et al.* (2005) have also used this approach in their modelling.[260] It is *very* important to note however that time series regression cannot predict the future. Fertility and mortality rates, for example, may change due to unforeseen factors such as a tightening of immigration policy, political instability, economic depression, the spread of disease, natural disasters, one-off health care advancements, war and so on. Being able to directly change exogenous variables such as fertility rates is therefore essential for simulation of Auckland Region's environment-economy system.

11.4 Labour Force Module

In this Section the labour force dynamics of the ARDEEM model are developed. The labour force module consists of no stocks or flows, but only of converters which transform the population module estimates into total available labour force (> 15 years of age), adjust these estimates for unemployment to derive FTE employment and, in turn, distribute this employment to economic industries. The employment by industry estimates are a critical factor input into the economic growth module of Section 11.5. The Vensim® system dynamics influence diagram for the labour force module is depicted in Figure 11.3. The mathematics of the module is given below:

[260] 'Curve fitting' approaches have also been extensively used by the Resource Futures Group at the CSIRO in Canberra. This group, led by Dr Barney Foran, has developed the Australian Stocks and Flows Model (ASFM) to simulate the resource requirements necessary to sustain the Australian economy to 2100 under particular policy driven scenarios.

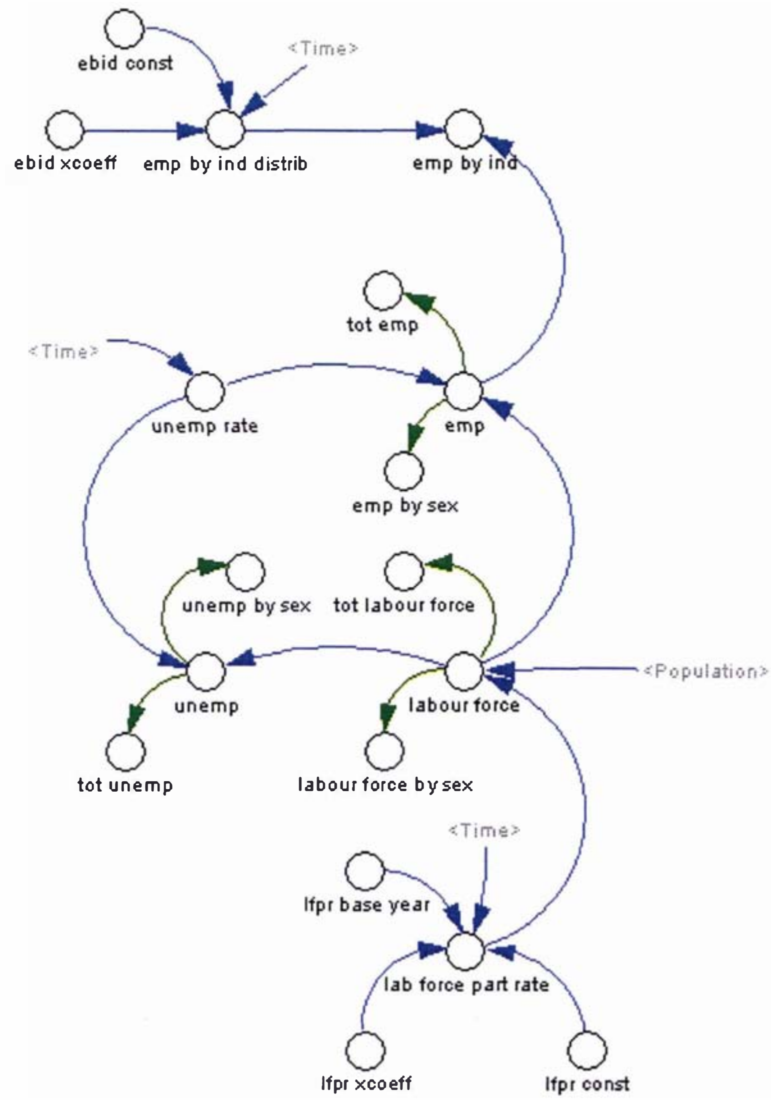

Figure 11.3 Labour Force Module Influence Diagram

Converters

lab force part rate$_{a,s}$ = (*lfpr xcoeff*$_{a,s}$ × LN((t) − *lfpr base year*$_{a,s}$)) + *lfpr const*$_{a,s}$. Labour force participation rates for those under 15 years of age are set to zero.

where:

lfpr base year$_{a,s}$ = the base year of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort. A 1986 base year was used for $a < 60$, and a 1993 base year for $a >= 60$.

lfpr const$_{a,s}$ = the constant of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort from the base year.

$lfpr\ xcoeff_{a,s}$	= the 'x' coefficient of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort from the base year.
$labour\ force_{a,s}$	= $Population_{a,s}(t) \times lab\ force\ part\ rate_{a,s}$. As measured in full-time equivalents (FTEs).
$emp_{a,s}$	= $labour\ force_{a,s} \times (1 - unemp\ rate_{a,s})$. As measured in FTEs.
where:	
$unemp\ rate_{a,s}$	= a graph depicting annual unemployment rates for New Zealand as taken from Statistics New Zealand. It is assumed that Auckland Region unemployment rates in each age-sex cohort are similar to those of the nation. Post-2005 unemployment rates for each age-sex cohort were derived using a moving average of the preceding 6 years.
$unemp_{a,s}$	= $labour\ force_{a,s} \times unemp\ rate_{a,s}$. As measured in FTEs.
$emp\ by\ ind_i$	= $\sum_{a=15}^{n} \sum_{s=f,m} (emp_{a,s}) \times emp\ by\ ind\ distrib_i$. As measured in FTEs.
where:	
$emp\ by\ ind\ distrib_i$	= $(ebid\ xcoeff_i \times \mathrm{LN}((t) - 1987)) + ebid\ const_i$
$ebid\ const_i$	= the constant of a logarithmic time series regression equation describing the distribution of employment (FTEs) across economic industries between 1987 and 2003.
$ebid\ xcoeff_i$	= the 'x' coefficient of a logarithmic time series regression equation describing the distribution of employment (FTEs) across economic industries between 1987 and 2003.

Reporting variables

$labour\ force\ by\ sex_s$	= $\sum_{a=15}^{n} (labour\ force_{a,s})$. Total labour force by sex (FTEs).
$tot\ unemp$	= $\sum_{a=15}^{n} \sum_{s=f,m} (unemp_{a,s})$. Total unemployment (FTEs).

unemp by sex$_s$ $= \sum_{a=15}^{n} (\,unemp_{a,s})$. Total unemployment by sex (FTEs).

tot labour force $= \sum_{a=15}^{n} \sum_{s=f,m} (\,tot\ labour\ force_{a,s})$. Total labour force (FTEs).

emp by sex$_s$ $= \sum_{a=15}^{n} (\,emp_{a,s})$. Total employment by sex (FTEs).

tot emp $= \sum_{a=15}^{n} \sum_{s=f,m} (\,emp_{a,s})$. Total employment (FTEs).

11.5 Growth Module

In this Section a growth model for ARDEEM is developed. The model builds on the economic growth theories critiqued in Chapter 10. Although several alternative growth models were operationalised and tested using hypothetical data, a severe paucity of actual data[261], along with time constraints, prohibited fuller implementations. One or two of these alternatives could arguably be considered to be more conceptually appealing than the actual model implemented below. One such alternative, an endogenous growth model, is depicted in Appendix L using a Vensim® system dynamics influence diagram.

At the core of the growth model is a production function controlling the estimation of future output by industry within the Auckland Region economy (Figure 11.4). The production function is comprised of factor inputs (manufactured capital, natural capital, labour, domestic commodity use, commodity imports, and technological change) which are determined through a number of dynamic feedback loops. The factor inputs and their loops are considered further below:

- *Capital.* This represents the stock of manufactured capital (covering intangible assets, plant and machinery, transport equipment, other construction, non-residential buildings, and residential buildings) utilised in producing economic output in the economy. Capital stock estimates for the base year were derived by scaling down national estimates to the Auckland Region based on FTE employment.[262] The national estimates were obtained from Statistics New Zealand (2000). Capital formation depends on

[261] An alternative engine based on endogenous growth theory, for example, required estimates of knowledge stocks, knowledge creation/duplication rates, and so on for the modelling of the 'stepping on toes' and 'standing on the shoulders of giants' technological spillover effects described in Chapter 10. A further complication, relevant to this example, was the necessity to build not only dynamics for knowledge creation occurring within the Auckland Region, but also for the rest of the world.

[262] It is assumed that the mix of capital used by each worker is spatially invariant across New Zealand.

economic output and an exogenously set investment rate, while capital depreciation depends on the size of the capital stock and an exogenously set depreciation rate. Capital investment and depreciation rates were developed by applying regression analysis to national time series obtained from Statistics New Zealand's INFOS database. Again, there is no reason why future patterns of investment and depreciation should reflect past trends. Furthermore, capital investment and the production of economic output are interdependent activities. The economic output of an industry includes wage, salary and dividend payments made to employees, which in turn, provides the fuel for further investment. Data constraints prohibited the explicit modelling of this feedback.[263]

- *Labour*. Labour inputs are included in ARDEEM through the estimation of the number of human hours worked annually in each industry. These estimates were generated by multiplying for each industry employment estimates by occupation (FTEs), by the number of hours typically worked in each week within each occupation (hours), and then scaling these to produce annual estimates. Measurement in human-hours accounts for productivity changes brought about by working more hours per day. Labour factor payments (i.e. wages and salaries) also play a critical role in ARDEEM, through namely: (1) investment in the formation of capital – as discussed above, and (2) commodity consumption – as captured in the positive feedback between the Economic and Growth modules involving the use_t variable.
- *Commodity use*. The criticality of minor factor inputs in generating an industry's output along with path dependencies are captured in the model by consideration of commodities used in intermediate consumption. Currently commodity inputs in ARDEEM are only considered in aggregate; it is envisaged that future versions of the model will consider more carefully the role played at a detailed commodity level.
- *Commodity imports*. Commodity imports are essential to the Auckland Region economy (refer to Chapters 5, 6 and 8 for further details).[264] Auckland Region's traditional role in import substitution was identified in Chapter 5, as was the increasing trade openness of the economy; particularly for light manufacturing industries. If local supply is unable to satisfy local demand for a particular commodity it is likely that the market response will be to import this commodity. Furthermore, if a locally provided

[263] Separation of domestic and foreign capital investment at a disaggregated sectoral level was the main constraint.

[264] This critical dependence has been further investigated by the author and Professor Le Heron of the School of Geography and Environmental Science at University of Auckland. Based on an analysis of changes in Auckland Region value added and employment multipliers between 1987 and 2003 it was found that economic interdependencies between industries had substantially weakened, while a compensatory growth in trade, particularly with neighbouring regions and Australia, had eventuated. Given the globalisation of international markets this is perhaps not surprising.

non-renewable resource becomes scarce, and cannot easily be substituted for, then importation of the resource will be critical for continued economic activity. Allowing for the possible simulation of substitution of domestic commodities for imported equivalents is therefore considered paramount. It is envisaged that in future versions of ARDEEM consideration will also be given to the demand for exports occurring elsewhere (refer to Appendix C for a detailed analysis of interregional trade flows).

- *Technology index.* This stock represents technological change over time via the positive feedback loop between the *Technology Index*$_i$ stock and the *technology formation*$_i$ flow. The formation rate is controlled by the exogenously determined *technology rate*$_i$. The technology rate for each industry was set equal to the 1998 to 2002 geometric annual average total factor productivity (TFP) rate as obtained from Black *et al.* (2003). Since the TFP covers all factor inputs the technology index must augment the entire production function. It should be noted that if each industry's TFP is set to zero then the reporting variables *output per worker*$_i$ and *capital per worker*$_i$ will tend toward a steady-state over the long term i.e. there will be no productivity growth and the growth rate of the Auckland Region economy will simply mirror the population growth rate. Again, it is important to note that future trends in TFP may not reflect historical trends.
- *Elasticities of output with respect to factor inputs* (a_i, b_i, g_i, and d_i). These elasticities were estimated by taking a 1987 to 2003 time series of the logs of the factor inputs (i.e. *Capital*$_i$, *emp by ind*$_i$, *use*$_i$, and *imports*$_i$) and performing a constrained regression such that the coefficients of the dependent variables of the regression equation (i.e. a_i, b_i, g_i, and d_i) summed to 1 (i.e. exhibited constant returns to scale). This approach is commonly used by economists to derive the elasticities of factor inputs with respect to output. It is important to note that the regression analysis is used only to establish the initial values of a_i, b_i, g_i, and d_i, i.e. it does not in any way mean that these elasticities will remain the same over the next 30 to 70 years. Furthermore, no assumptions have been made as to how one factor input may substitute for another; instead these may be tested explicitly under various simulations.

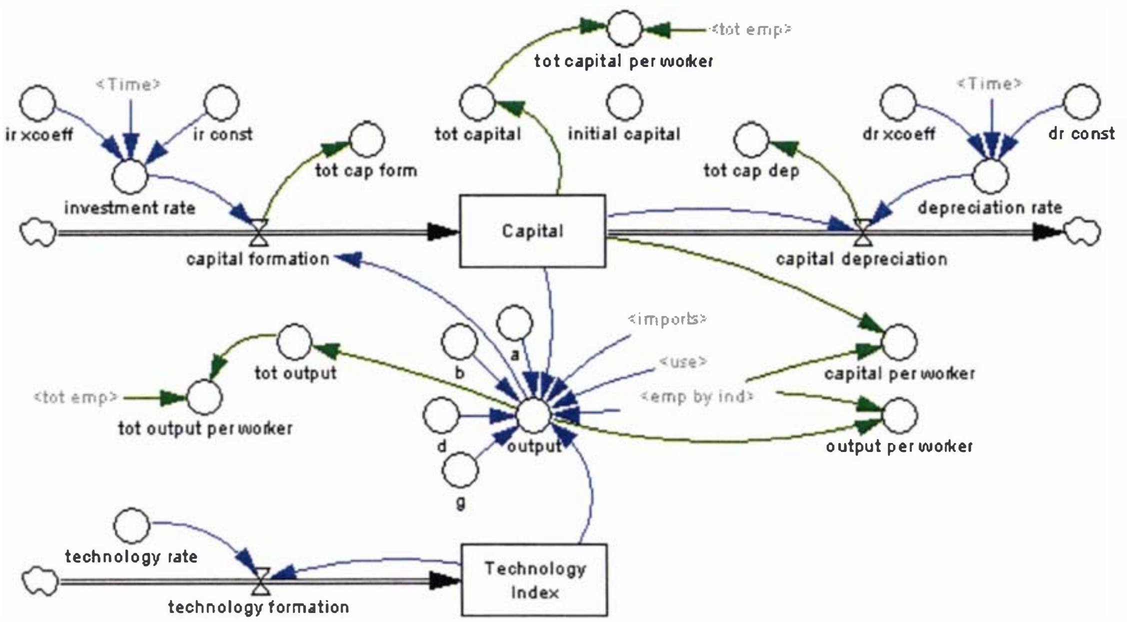

Figure 11.4 Growth Module Influence Diagram

Capital Stock

$Capital_i\ (t + dt)$ $= Capital_i(t) + (capital\ formation_i - capital\ depreciation_i) \times dt.$ The total available manufactured capital stock ($ mil)[265] utilised by industry *i*.

where:

Initial $Capital_i$ $= initial\ capital_i$ ($ mil) for the 1998 base year.

Inflows

$capital\ formation_i$ $= output_i \times investment\ rate_i$. As measured in $ mil.

where:

$investment\ rate_i$ $= (ir\ xcoeff_i \times \mathrm{LN}((t) - 1987)) + ir\ const_i$

where:

$ir\ xoceff_i$ = the 'x' coefficient of a linear or logarithmic time series regression equation describing the rate of capital investment by industry *i* between 1987 and 2003.

$ir\ const_i$ = the constant of a linear or logarithmic time series regression equation describing the rate of capital investment by industry *i* between 1987 and 2003.

[265] All financial values are in $1995 unless stated otherwise.

output$_i$ = $((Technology\ Index_i(t) \times Capital_i(t))^{a_i}) \times ((Technology\ Index_i(t) \times emp\ by\ ind_i)^{b_i}) \times ((\sum_{imp=1}^{n}(imports_{imp,i}) \times Technology\ Index_i\ (t))^{g_i}) \times ((\sum_{c=1}^{n}(use_{c,i}) \times Technology\ Index_i(t))^{d_i})$. A production function estimating total output ($ mil) in each industry i. The production function assumes constant returns to scale (i.e. $a_i + b_i + g_i + d_i = 1$).

where:

a_i = the elasticity of output with respect to capital utilised by industry i.

b_i = the elasticity of output with respect to employment utilised by industry i.

g_i = the elasticity of output with respect to total imports utilised by industry i.

d_i = the elasticity of output with respect to total intermediate commodity use by industry i.

$imports_{imp,i}$ = total imports ($ mil) used by industry i.

$use_{c,i}$ = total commodities ($ mil) used by industry i.

Outflows

capital depreciation$_i$ = $Capital_i(t) \times depreciation\ rate_i$ As measured in $ mil.

where:

depreciation rate$_i$ = $dr\ xcoeff_i \times \mathrm{LN}((t) - 1972) + dr\ const_i$

where:

dr xcoeff$_i$ = the 'x' coefficient of a linear or logarithmic time series regression equation describing the rate of capital depreciation by industry i between 1972 and 2003.

dr const$_i$ = the constant of a linear or logarithmic time series regression equation describing the rate of capital depreciation by industry i between 1972 and 2003.

Technology Index Stock

$Technology\ Index_i\ (t + dt)$ = $Technology\ Index_i(t) + (technology\ formation_i) \times dt$

where:

Initial *Technology Index* = 1 for the 1998 base year.

Inflows

technology formation$_i$ = *Technology Index$_i$(t)* × *technology rate$_i$*

where:

technology rate$_i$ = the geometric rate of annual technological change for industry *i*. Black *et al.* (2003) have estimated total factor productivity by industry in the New Zealand economy over the period 1988 to 2002. These estimates are used here as a proxy for the rate of technological change in the Auckland Region economy.

Reporting variables

tot cap form = $\sum_{i=1}^{n}(\textit{capital formation}_i)$. Total capital formation ($ mil).

tot cap dep = $\sum_{i=1}^{n}(\textit{capital depreciation}_i)$. Total capital depreciation ($ mil).

tot capital = $\sum_{i=1}^{n}(\textit{Capital}_i(t))$. Total capital ($ mil).

tot capital per worker = IF THEN ELSE(*tot emp* = 0, 0, *tot capital* / *tot emp*). As measured in $ mil.

tot output per worker = IF THEN ELSE(*tot emp* = 0, 0, *tot output* / *tot emp*). As measured in $ mil.

tot output = $\sum_{i=1}^{n}(\textit{output}_i)$. Total output ($ mil).

capital per worker$_i$ = IF THEN ELSE(*emp by ind$_i$* = 0, 0, *Capital$_i$(t)* / *emp by ind$_i$*). Total capital ($ mil) by industry *i*.

output per worker$_i$ = IF THEN ELSE(*emp by ind$_i$* = 0, 0, *output$_i$* / *emp by ind$_i$*). Total output ($ mil) by industry *i*.

11.6 Economic Module

The economic module consists of a commodity by industry input-output economic system (compatible with Table 4.1). This module describes the circular flow of commodities supplied both domestically and internationally, and their corresponding use and final consumption (Figure 11.5). The module is linked with the growth module through a number of positive (reinforcing) feedbacks. On the one hand, it provides key inputs into the growth module by generating estimates of (1) commodity imports required to satisfy both intermediate and final demand, and (2) intermediate demand commodity use. On the other hand, it utilises estimates of output and capital formation in the calculation of the interregional exports, international exports and other final demands (capital formation).

There are several key features of the economic module. Firstly, utilising the input-output model conceptualised in Chapter 4, and implemented in Chapter 5, allows the interrelationships between economic industries to be simulated over time. If, for example, households consume more dairy products, then the model would simulate not only a resultant increase in dairy product manufacture, but also an increase in dairy cattle farming.[266] Secondly, the input-output model is created in a commodity-by-industry format which records joint production. Although data constraints will typically restrict the simulation to less than 50 industries, the number of commodities will be far less restricted; the supply and use of hundreds of commodities could be simulated without difficulty. Thirdly, this detailed consideration of industries and their commodities potentially enables the unique role played by manufacturing in capital formation to be directly incorporated in the growth module production function. It also permits consideration of minor, but limiting or critical commodity factor inputs, to be incorporated in the production function. Fourthly, the adoption of a financial commodity-by-industry framework ensures comparability and the straightforward translation into physical equivalents (see Section 11.7 below). Finally, the commodity-by-industry format permits the computation of economic and ecological multipliers (and by corollary ecological footprints) at each time step. Overall, the economic module combines the detailed commodity-by-industry input-output data with the flexibility of dynamic simulation.

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[266] These relationships are evaluated at each time step within the model. It should be noted however that the input mix of commodities (i.e. purchase pattern) utilised by each industry is assumed to remain constant over time. A more complete implementation of the model would allow this mix to change over time. Duchin and Szyld (1985) and Leontief and Duchin (1986) have, for example, performed time series regression on input-output technical coefficients to assess the future impact of automation on workers. This approach, while beyond the scope of this thesis, provides a possible pathway for the future development of the economic module.

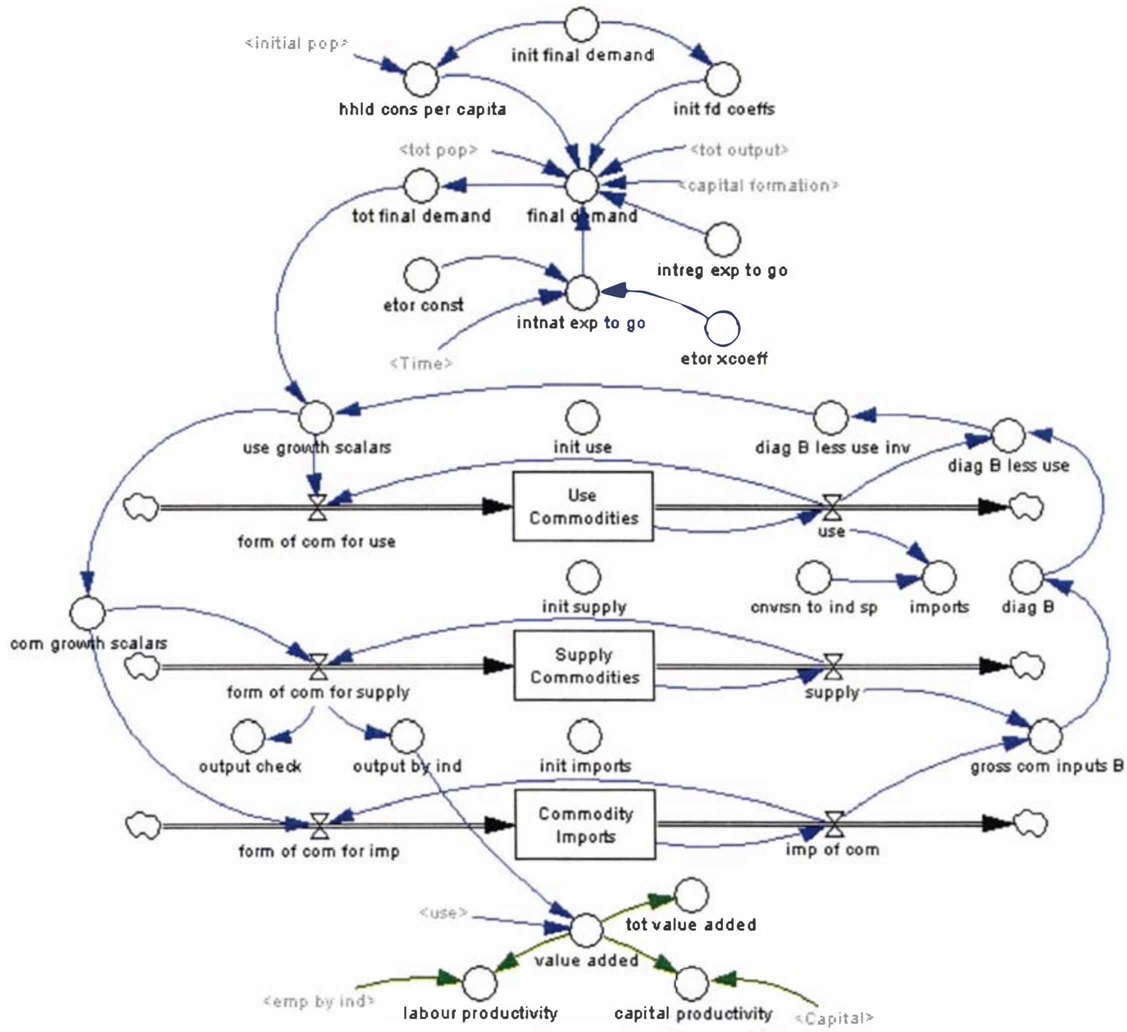

Figure 11.5 Economic Module Influence Diagram

Use Commodities Stock

$Use\ Commodities_{c,i}\ (t + dt)$ = $Use\ Commodities_{c,i}(t)$ + ($form\ of\ com\ for\ use_{c,i} - use_{c,i}$) × dt.
As measured in $ mil.

where:

Initial $Use\ Commodities_{c,i}$ = $init\ use_{c,i}$ ($ mil) for the 1998 base year.

Inflow

$form\ of\ com\ for\ use_{c,i}$ = $use_{c,i} \times use\ growth\ scalars_{i}$ As measured in $ mil.

where:

$use\ growth\ scalars_{Ind01}$ = $((diag\ B\ less\ use\ inv_{Com01,Ind01} \times tot\ final\ demand_{Com01}) + (diag\ B\ less\ use\ inv_{Com01,Ind02} \times tot\ final\ demand_{Com02}) + (diag\ B\ less\ use\ inv_{Com01,Ind03} \times tot\ final\ demand_{Com03}))$[267]

$use\ growth\ scalars_{Ind02}$ = $((diag\ B\ less\ use\ inv_{Com02,Ind01} \times tot\ final\ demand_{Com01}) + (diag\ B\ less\ use\ inv_{Com02,Ind02} \times tot\ final\ demand_{Com02}) + (diag\ B\ less\ use\ inv_{Com02,Ind03} \times tot\ final\ demand_{Com03}))$

$use\ growth\ scalars_{Ind03}$ = $((diag\ B\ less\ use\ inv_{Com03,Ind01} \times tot\ final\ demand_{Com01}) + (diag\ B\ less\ use\ inv_{Com03,Ind02} \times tot\ final\ demand_{Com02}) + (diag\ B\ less\ use\ inv_{Com03,Ind03} \times tot\ final\ demand_{Com03}))$

$diag\ B\ less\ use\ inv_{c,i}$ = INVERT MATRIX($diag\ B\ less\ use_{c,i}$, 3)

$diag\ B\ less\ use_{c,i}$ = $diag\ B_{c,i} - use_{c,i}$

$diag\ B_{c,i}$ = $gross\ com\ inputs_c$. As measured in \$ mil.

$gross\ com\ inputs\ B_c$ = $\sum_{i=1}^{n}(supply_{i,c}) + \sum_{imp=1}^{n}(imp\ of\ com_{imp,c})$. Total gross commodity inputs (\$ mil).

$tot\ final\ demand_c$ = $\sum_{f=1}^{n}(final\ demand_{c,f})$. Total final demand (\$ mil) by commodity c.

$final\ demand_{c,HhldCons}$ = $hhld\ cons\ per\ capita_c \times tot\ pop$. As measured in \$ mil.

$final\ demand_{c,OFD}$ = $init\ fd\ coeffs_{c,OFD} \times \sum_{i=1}^{n}(capital\ formation_i)$. As measured in \$ mil.

$final\ demand_{c,IntRegExp}$ = $init\ fd\ coeffs_{c,IntRegExp} \times tot\ output \times intreg\ exp\ to\ go$. As measured in \$ mil.

$final\ demand_{c,IntNatExp}$ = $init\ fd\ coeffs_{c,IntNatExp} \times tot\ output \times intnat\ exp\ to\ go$. As measured in \$ mil.

intnat exp to go = $(etor\ xcoeff \times \mathrm{LN}((t) - 1987)) + etor\ const$

etor const = the constant of a logarithmic time series regression equation describing the ratio of international exports to gross output between 1987 and 2003.

etor xcoeff = the 'x' coefficient of a logarithmic time series regression equation describing the ratio of international exports to gross output between 1987 and 2003.

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[267] This equation along with the two that follow represents a matrix multiplication of *diag B less use inv* by *tot final demand*.

intreg exp to go = the ratio of interregional exports to gross output for the 1998 year.

init fd coeffs$_{c,f}$ = $\textit{init final demand}_{c,f} \,/\, \sum_{c=1}^{n}(\textit{init final demand}_{c,f})$

init final demand$_{c,f}$ = final demand consumption by commodity *c* across final demand *f* for the 1998 base year ($ mil).

hhlds cons per capita$_c$ = $\textit{init final demand}_{c,HhldCons} \,/\, \sum_{a,s}(\textit{initial pop}_{a,s})$. As measured in $ mil.

Outflow

use$_{c,i}$ = *Use Commodities*$_{c,i}(t)$. As measured in $ mil.

imports$_{imps,i}$ = $(\textit{cnvrsn to ind sp}_{imp,Com01} \times \textit{use}_{Com01,i}) + (\textit{cnvrsn to ind sp}_{imp,Com02} \times \textit{use}_{Com02,i}) + (\textit{cnvrsn to ind sp}_{imp,Com03} \times \textit{use}_{Com03,i})$. Repeat for $c = 1$ to n. As measured in $ mil.

cnvsrn to ind sp$_{imps,c}$ = a matrix for converting imports from commodity to industry space for the 1998 base year. This matrix was derived from the Auckland Region input-output model developed in Chapter 5 by applying the procedure outlined in Section 4.4.3.2.

Supply Commodities Stock

Supply Commodities$_{i,c}(t + dt)$ = *Supply Commodities*$_{i,c}(t)$ + (*form of com for supply*$_{i,c}$ – *supply*$_{i,c}$) × *dt*. As measured in $ mil.

where:

Initial *Supply Commodities*$_{i,c}$ = *init supply*$_{i,c}$ for the 1998 base year ($ mil).

Inflow

form of com for supply$_{i,c}$ = *supply*$_{i,c}$ × *com growth scalars*$_c$. As measured in $ mil.

where:

com growth scalars$_c$ = *use growth scalars*$_i$

Outflow

supply$_{i,c}$ = *Supply Commodities*$_{i,c}(t)$. As measured in $ mil.

Commodity Imports Stock

Commodity Imports$_{imp,c}$ $(t + dt)$ = *Commodity Imports*$_{imp,c}(t)$ + (*form of com for imp*$_{imp,c}$ – *imp of com*$_{imp,c}$) × *dt*. As measured in \$ mil.

where:

Initial *Commodity Imports*$_{imp,c}$ = *init imports*$_{imp,c}$ for the 1998 base year (\$ mil).

<u>Inflow</u>

form of com for imp$_{imp,c}$ = *imp of com*$_{imp,c}$ × *com growth scalars*$_c$. As measured in \$ mil.

<u>Outflow</u>

imp of com$_{imp,c}$ = *Commodity Imports*$_{imp,c}(t)$. As measured in \$ mil.

Reporting variables

output check = $\sum_{i,c}$(*form of com for supply*$_{i,c}$). Total output check (\$ mil).

output by ind$_i$ = $\sum_{c=1}^{n}$(*form of com for supply*$_{i,c}$). Total output by industry i (\$ mil).

value added$_i$ = *output by ind*$_i$ – $\sum_{c=1}^{n}$(*use*$_{c,i}$). Total value added by industry i (\$ mil).

tot value added = $\sum_{i=1}^{n}$(*value added*$_i$). Total value added (\$ mil).

labour productivity$_i$ = IF THEN ELSE(*emp by ind*$_i$ = 0, 0, *value added*$_i$ / *emp by ind*$_i$). Labour productivity as measured in \$ mil.

capital productivity$_i$ = IF THEN ELSE(*Capital*$_i(t)$ = 0, 0, *value added*$_i$ / *Capital*$_i(t)$). Capital productivity as measured in \$ mil.

11.7 Economic Physical Flow Module

The economic physical flow module is the physical equivalent of the economic flow module. It describes the Auckland Region economy in physical (mass) flow terms, including commodity supply, use, imports and exports (Figure 11.6). The module focuses purely on the within economy physical flows. Financial estimates of commodity supply, use, imports and exports are converted to physical equivalents based on price ($ per tonne) and eco-efficiency indices which allow for technological improvements.[268] The module utilises within economy data from the financial input-output model conceptualised in Table 4.1 and implemented in Chapter 5, and the physical input-output model conceptualised in Table 4.2 and implemented in Chapter 6.

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[268] It is assumed that these technological improvements occur at a constant compounding rate. This simplifying assumption has been adopted to demonstrate how technological change might be incorporated within ARDEEM, but is considered questionable given long-run thermodynamic constraints.

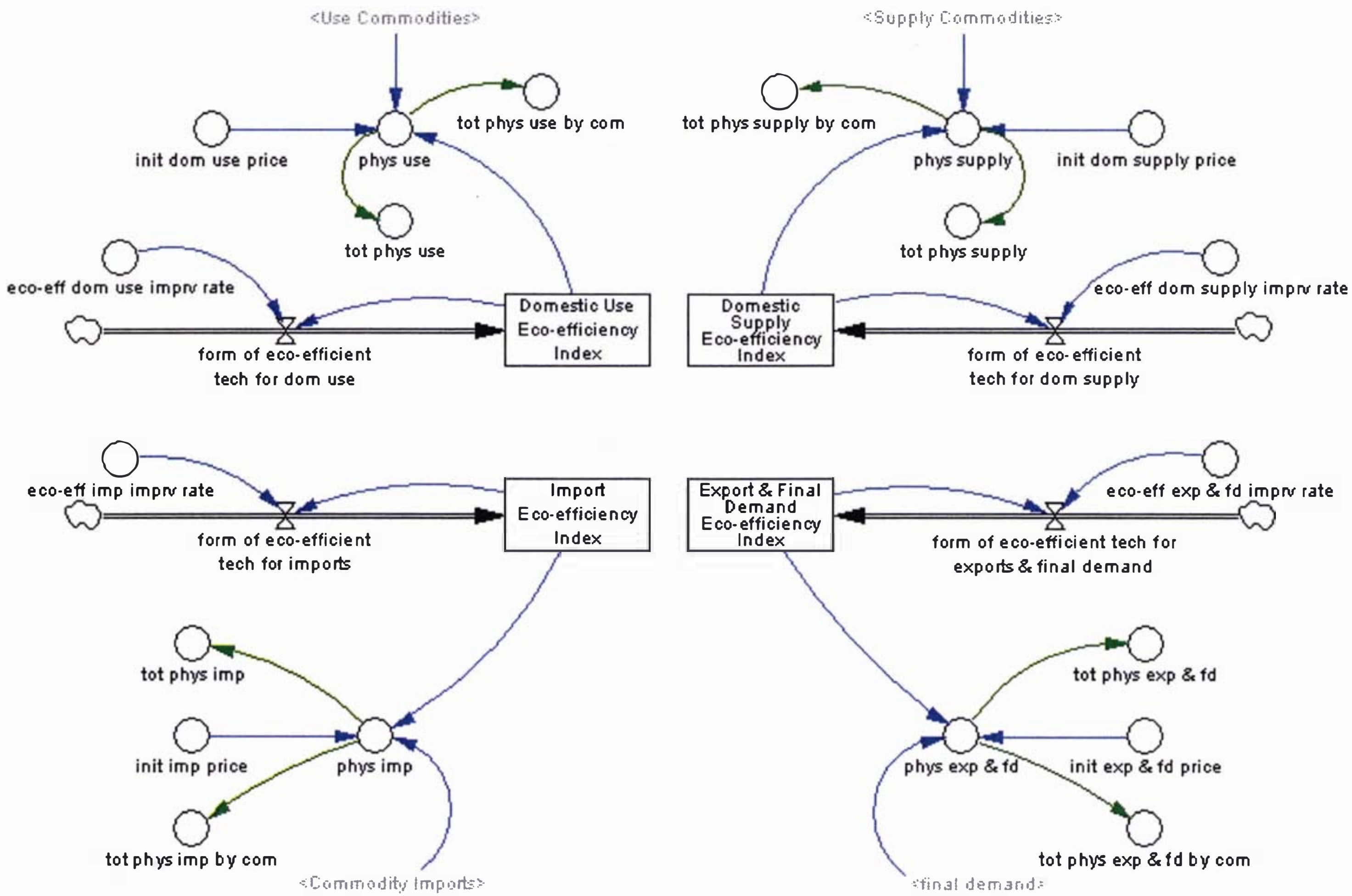

Figure 11.6 Economic Physical Flow Influence Diagram

Domestic Use Eco-efficiency Index Stock

Domestic Use Eco-efficiency Index$_{c,i}$ $(t + dt)$ = *Domestic Use Eco-efficiency Index*$_{c,i}(t)$ + (*form of eco-efficient tech for dom use*$_{c,i}$) $\times$ *dt*

where:

Initial *Domestic Use Eco-efficiency Index*$_{c,i}$ = 1 for the 1998 base year.

Inflow

form of eco-efficient tech for dom use$_{c,i}$ = *Domestic Use Eco-efficiency Index*$_{c,i}(t)\times$ *eco-eff dom use imprv rate*$_{c,i}$

eco-eff dom use imprv rate$_{c,i}$ = the rate of eco-efficiency improvements in domestic use of commodity *c* by industry *i*. This rate is assumed to compound over time through technological change.[269]

phys use$_{c,i}$ = IF THEN ELSE (*init dom use price*$_{c,i}$ = 0, 0, ((*Use Commodities*$_{c,i}(t)$ $\times$ 1000000) / *init dom use price*$_{c,i}$) $\times$ *Domestic Use Eco-efficiency Index*$_{c,i}(t)$). As measured in tonnes.

init dom use price$_{c,i}$ = the 1998 \$ per tonne price used to convert the domestic use of commodity *c* by industry *i*, as recorded in financial terms, into a physical equivalent.

Domestic Supply Eco-efficiency Index Stock

Domestic Supply Eco-efficiency Index$_{i,c}$ $(t + dt)$ = *Domestic Supply Eco-efficiency Index*$_{i,c}(t)$ + (*form of eco-efficient tech for dom supply*$_{i,c}$) $\times$ *dt*

Initial *Domestic Supply Eco-efficiency Index*$_{i,c}$ = 1 for the 1998 base year.

[269] This simplifying assumption has been adopted to demonstrate how eco-efficiency improvements might be included within ARDEEM, but is considered questionable given long-run thermodynamic limits to technological change. This assumption also applies to the following variables within this module: *eco-eff dom supply imprv rate*$_{i,c}$, *eco-eff imp imprv rate*$_{imp,c}$, and *eco-eff exp & fd imprv rate*$_{c,f}$.

Inflow

form of eco-efficient tech for dom supply$_{i,c}$	= *Domestic Supply Eco-efficiency Index*$_{i,c}(t)$ × *eco-eff dom supply imprv rate*$_{i,c}$
eco-eff dom supply imprv rate$_{i,c}$	= the rate of eco-efficiency improvements in domestic supply of commodity *c* by industry *i*.
phys supply$_{i,c}$	= IF THEN ELSE(*init dom supply price*$_{i,c}$ = 0, 0, ((*Supply Commodities*$_{i,c}(t)$ × 1000000) / *init dom supply price*$_{i,c}$) × *Domestic Supply Eco-efficiency Index*$_{i,c}(t)$). As measured in tonnes.
init dom supply price$_{i,c}$	= the 1998 $ per tonne price used to convert the domestic supply of commodity *c* by industry *i*, as recorded in financial terms, into a physical equivalent.

Import Eco-efficiency Index Stock

Import *Eco-efficiency Index*$_{imp,c}$ $(t + dt)$	= *Import Eco-efficiency Index*$_{imp,c}(t)$ + (*form of eco-efficient tech for imports*$_{imp,c}$) × dt
Initial *Import Eco-efficiency Index*$_{imp,c}$	= 1 for the 1998 base year.

Inflow

form of eco-efficient tech for imports$_{imp,c}$	= *Import Eco-efficiency Index*$_{imp,c}(t)$ × *eco-eff imp imprv rate*$_{imp,c}$
eco-eff imp imprv rate$_{imp,c}$	= the rate of eco-efficiency improvements in imported commodity *c*.
phys imp$_{imp,c}$	= IF THEN ELSE(*init imp price*$_{imp,c}$ = 0, 0, ((*Commodity Imports*$_{imp,c}(t)$ × 1000000) / *init imp price*$_{imp,c}$) × *Import Eco-efficiecy Index*$_{imp,c}(t)$). As measured in tonnes.
init imp price$_{imp,c}$	= the 1998 $ per tonne price used to convert the commodity *c* imports by industry *i*, as recorded in financial terms, into a physical equivalent.

Export & Final Demand Eco-efficiency Index Stock

Export & Final Demand Eco-efficiency Index$_{c,f}$ $(t + dt)$ = *Export & Final Demand Eco-efficiency Index*$_{c,f}(t)$ + (*form of eco-efficient tech for exports & final demand*$_{c,f}$) × *dt*

Initial *Export & Final Demand Eco-efficiency Index*$_{c,f}$ = 1 for the 1998 base year.

Inflow

form of eco-efficient tech for exports & final demand$_{c,f}$ = *Export & Final Demand Eco-efficiency Index*$_{c,f}(t)$ × *eco-eff exp & fd imprv rate*$_{c,f}$

eco-eff exp & fd imprv rate$_{c,f}$ = the rate of eco-efficiency improvements in commodity *c* destined for final demand category *f*.

phys exp & fd$_{c,f}$ = IF THEN ELSE(*init exp & fd price*$_{c,f}$ = 0, 0, ((*final demand*$_{c,f}$ × 1000000) / *init exp & fd price*$_{c,f}$) × *Export & Final Demand Eco-efficiency Index*$_{c,f}(t)$). As measured in tonnes.

init exp & fd price$_{c,f}$ = the 1998 $ per tonne price used to convert the commodity *c* used by final demand category *f*, as recorded in financial terms, into a physical equivalent.

Reporting variables

tot phys use = $\sum_{c,i}(\textit{phys use}_{c,i})$. The total physical use of commodities within the economy (tonnes).

tot phys use by com$_c$ = $\sum_{i=1}^{n}(\textit{phys use}_{c,i})$. The total physical use of commodity *c* within the economy (tonnes).

tot phys supply = $\sum_{i,c}(\textit{phys supply}_{i,c})$. The total physical supply of commodities within the economy (tonnes).

tot phys supply by com$_c$ $= \sum_{i=1}^{n}(phys\ supply_{i,c})$. The total physical supply of commodity *c* within the economy (tonnes).

tot phys imp $= \sum_{imp,c}(phys\ imp_{imp,c})$. The total physical imports from other economies (tonnes).

tot phys imp by com$_c$ $= \sum_{imp=1}^{n}(phys\ imp_{imp,c})$. The total physical import of commodity *c* from other economies (tonnes).

tot phys exp & fd $= \sum_{c,f}(phys\ exp\ \&\ fd_{c,f})$. The total physical exports to other economies plus domestic final consumption (tonnes).

tot phys exp & fd by com$_c$ $= \sum_{f=1}^{n}(phys\ exp\ \&\ fd_{c,f})$. The total physical export and final consumption of commodity *c* (tonnes).

11.8 Environment-Economy Physical Flow Module

This module describes the physical flow of raw materials and residuals associated with economic activity in the Auckland Region (Figure 11.7). The module focuses on the physical flow of ecological commodities crossing the environment-economy system boundary (refer to Figure 4.8). This is largely made up of physical flows of commodities not conventionally measured in economic markets. This module, like the economic physical flow module, draws on output by industry estimates generated by the growth module, exogenous estimates of raw material use/residual generation per $ output (as generated in Chapters 6), and indices of improvements in eco-efficiency[270] to establish the physical flow of raw material and residuals. The module utilises raw material and residual data from the physical input-output model presented in Table 4.2, and implemented in Chapter 6.

[270] It is assumed that these technological improvements occur at a constant compounding rate. This simplifying assumption has been adopted to demonstrate how technological change might be incorporated within ARDEEM, but is considered questionable given long-run thermodynamic constraints.

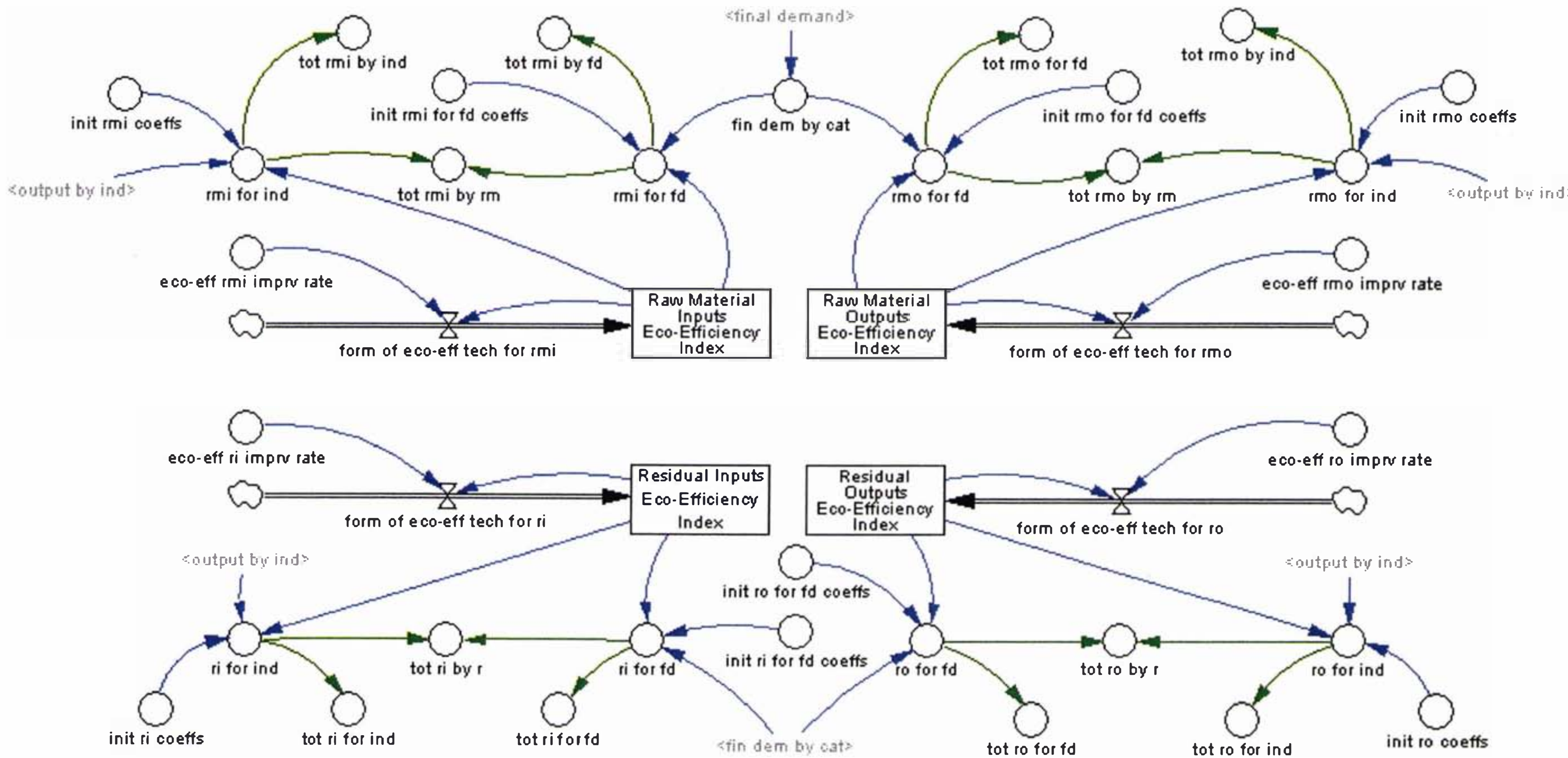

Figure 11.7 Environment-Economy Physical Flow Influence Diagram

Raw Material Inputs Eco-Efficiency Index Stock

Raw Material Inputs Eco-Efficiency $Index_{rm}$ $(t + dt)$ = *Raw Material Inputs Eco-Efficiency* $Index_{rm}(t)$ + (*form of eco-eff tech for* rmi_{rm}) × *dt*

where:

Initial *Raw Material Inputs Eco-Efficiency* $Index_{rm}$ = 1 for the 1998 base year.

Inflow

form of eco-eff tech for rmi_{rm} = *Raw Material Inputs Eco-Efficiency* $Index_{rm}(t)\times$ *eco-eff rmi imprv* $rate_{rm}$

eco-eff rmi imprv $rate_{rm}$ = the rate of eco-efficiency improvements in the use of raw material input *rm*. This rate is assumed to compound over time through technological change.[271]

rmi for $ind_{rm,i}$ = *init rmi* $coeffs_{rm,i}$ × *output by* ind_i × *Raw Material Inputs Eco-Efficiency* $Index_{rm}(t)$. As measured in tonnes.

init rmi $coeffs_{rm,i}$ = the 1998 physical input of raw material *rm* (tonnes) required to produce $ of output in industry *i*.

rmi for $fd_{rm,f}$ = *init rmi for fd* $coeffs_{rm,f}$ × *fin dem by* cat_f × *Raw Material Inputs Eco-Efficiency* $Index_{rm}(t)$. As measured in tonnes.

init rmi for fd $coeffs_{rm,f}$ = the 1998 physical input of raw material *rm* (tonnes) required for consumption of $ of output in final demand category *f*.

fin dem by cat_f = $\sum_{c=1}^{n}(final\ demand_{c,f})$. Total final demand by category *f* ($ mil).

[271] This simplifying assumption has been adopted to demonstrate how eco-efficiency improvements might be included within ARDEEM, but is considered questionable given long-run thermodynamic limits to technological change. This assumption also applies to the following variables within this module: *eco-eff rmo imprv* $rate_{rm}$, *form of eco-eff tech for* ri_r and *eco-eff ro imprv* $rate_r$.

Raw Material Outputs Eco-Efficiency Index Stock

Raw Material Outputs Eco-Efficiency Index$_{rm}$ *(t + dt)* = *Raw Material Outputs Eco-Efficiency Index*$_{rm}$*(t)* + *(form of eco-eff tech for rmo*$_{rm}$*)* × *dt*

where:

Initial *Material Outputs Eco-Efficiency Index*$_{rm}$ = 1 for the 1998 base year.

Inflow

form of eco-eff tech for rmo$_{rm}$ = *Raw Material Outputs Eco-Efficiency Index*$_{rm}$ × *eco-eff rmo imprv rate*$_{rm}$*(t)*

eco-eff rmo imprv rate$_{rm}$ = the rate of eco-efficiency improvements in the supply of raw material output *rm*.

rmo for ind$_{i,rm}$ = *init rmo coeffs*$_{i,rm}$ × *output by ind*$_i$ × *Raw Material Outputs Eco-Efficiency Index*$_{rm}$*(t)*. As measured in tonnes.

init rmo coeffs$_{i,rm}$ = the 1998 physical output of raw material *rm* (tonnes) generated in producing $ of output in industry *i*.

rmo for fd$_{f,rm}$ = *init rmo for fd coeffs*$_{f,rm}$ × *fin dem by cat*$_f$ × *Raw Material Outputs Eco-Efficiency Index*$_{rm}$*(t)*. As measured in tonnes.

init rmo for fd coeffs$_{f,rm}$ = the 1998 physical output of raw material *rm* (tonnes) generated in consuming $ of output in final demand category *f*.

Residual Inputs Eco-Efficiency Index Stock

Residual Inputs Eco-Efficiency Index$_r$ *(t + dt)* = *Residual Inputs Eco-Efficiency Index*$_r$*(t)*+ *(form of eco-eff tech for ri*$_r$*)* × *dt*

where:

Initial *Residual Inputs Eco-Efficiency Index*$_r$ = 1 for the 1998 base year.

Inflow

form of eco-eff tech for ri_r = *Residual Inputs Eco-Efficiency* $Index_r(t)$ × *eco-eff ri imprv* $rate_r$

eco-eff ri imprv $rate_r$ = the rate of eco-efficiency improvements in the use of residual input *r*.

ri for $ind_{r,i}$ = *init ri* $coeffs_{r,i}$ × *output by* ind_i × *Residual Inputs Eco-Efficiency* $Index_r(t)$. As measured in $ mil.

init ri $coeffs_{r,i}$ = the 1998 physical input of residual *r* (tonnes) required to produce $ of output in industry *i*.

ri for $fd_{r,f}$ = *init ri for fd* $coeffs_{r,f}$ × *fin dem by* cat_f × *Residual Inputs Eco-Efficiency* $Index_r(t)$. As measured in tonnes.

init ri for fd $coeffs_{r,f}$ = the 1998 physical input of residual *r* (tonnes) required for consumption of $ of output in final demand category *f*.

Residual Outputs Eco-Efficiency Index Stock

Residual Outputs Eco-Efficiency $Index_r(t + dt)$ = *Residual Outputs Eco-Efficiency* $Index_r(t)$ + (*form of eco-eff tech for* ro_r) × *dt*

where:

Initial *Residual Outputs Eco-Efficiency* $Index_r$ = 1 for the 1998 base year.

Inflow

form of eco-eff tech for ro_r = *Residual Outputs Eco-Efficiency* $Index_r(t)$ × *eco-eff ro imprv* $rate_r$

eco-eff ro imprv $rate_r$ = the rate of eco-efficiency improvements in the supply of residual output *r*.

ro for $ind_{i,r}$ = *init ro* $coeffs_{i,r}$ × *output by* ind_i × *Residual Outputs Eco-Efficiency* $Index_r(t)$. As measured in tonnes.

init ro $coeffs_{i,r}$ = the 1998 physical output of residual *r* (tonnes) generated in producing $ of output in industry *i*.

ro for fd$_{f,r}$ = *init ro for fd coeffs*$_{f,r}$ × *fin dem by cat*$_{f}$ × *Residual Outputs Eco-Efficiency Index*$_{r}(t)$. As measured in tonnes.

init ro for fd coeffs$_{f,r}$ = the 1998 physical output of residual *r* (tonnes) generated in consuming \$ of output in final demand category *f*.

Reporting variables

tot rmi by rm$_{rm}$ = $\sum_{f=1}^{n}(\textit{rmi for fd}_{rm,f}) + \sum_{i=1}^{n}(\textit{rmi for ind}_{rm,i})$. Total physical input of raw material *rm* (tonnes) into the economy.

tot rmo by rm$_{rm}$ = $\sum_{f=1}^{n}(\textit{rmo for fd}_{f,rm}) + \sum_{i=1}^{n}(\textit{rmo for ind}_{i,rm})$. Total physical output of raw material *rm* (tonnes) from the economy.

tot ri by r$_{r}$ = $\sum_{f=1}^{n}(\textit{ri for fd}_{r,f}) + \sum_{i=1}^{n}(\textit{ri for ind}_{r,i})$. Total physical input of residual *r* (tonnes) into the economy.

tot ro by r$_{r}$ = $\sum_{f=1}^{n}(\textit{ro for fd}_{f,r}) + \sum_{i=1}^{n}(\textit{ro for ind}_{i,r})$. Total physical output of residual *r* (tonnes) from the economy.

tot rmi by ind$_{i}$ = $\sum_{rm=1}^{n}(\textit{rmi for ind}_{rm,i})$. Total physical input of raw materials into industry *i* (tonnes).

tot rmi by fd$_{f}$ = $\sum_{rm=1}^{n}(\textit{rmi for fd}_{f,rm})$. Total physical input of raw materials into final demand category *f* (tonnes).

tot rmo for fd$_{f}$ = $\sum_{rm=1}^{n}(\textit{rmo for fd}_{f,rm})$. Total physical output of raw materials from final demand category *f* (tonnes).

tot rmo by ind$_i$ $= \sum_{rm=1}^{n} (rmo\ for\ ind_{i,rm})$. Total physical output of raw materials from industry *i* (tonnes).

tot ri for ind$_i$ $= \sum_{r=1}^{n} (ri\ for\ ind_{r,i})$. Total physical input of residuals into industry *i* (tonnes).

tot ri for fd$_f$ $= \sum_{r=1}^{n} (ri\ for\ fd_{r,f})$. Total physical input of residuals into final demand category *f* (tonnes).

tot ro for fd$_f$ $= \sum_{r=1}^{n} (ro\ for\ fd_{f,r})$. Total physical output of residuals from final demand category *f* (tonnes).

tot ro for ind$_i$ $= \sum_{r=1}^{n} (ro\ for\ ind_{i,r})$. Total physical output of residuals from industry *i* (tonnes).

11.9 Validation and Verification of ARDEEM

Several steps were undertaken during the modelling process to ensure that the results generated by ARDEEM were as valid as possible. These are considered below in terms of structural and predictive validity.

11.9.1 Structural Validity of ARDEEM

Structural validity refers to the logic, consistency and accuracy of the model's internal structure i.e. its equations, interrelationships, and units of measurement. The structural validity of ARDEEM was evaluated by:

- *Creation of 1998 reference mode*. Simulation results generated for the 1998 base year were compared with actuals or estimates generated independently in Microsoft Excel®; particular emphasis was placed on the validity of endogenous variables.
- *Independent peer review*. The relationships within the model were independently peer reviewed by Professor Murray Patterson (School of People, Environment and Planning, Massey University), Professor Richard Le Heron (School of Geography and Environmental Science, University of Auckland), Dr Doug Fairgray (Economist, Market Economics Ltd) and Mr Geoff Butcher (Economist, Butcher Partners Ltd). In

light of these peer reviews several changes were made to the conceptualisation of ARDEEM.

11.9.2 Predictive Validity of ARDEEM

Predictivity validity refers to the model's ability to adequately imitate the behaviour of the real system. Predictive validity is however of only limited usefulness as a model may produce results which provide an extremely good historical data fit, but may in no way reflect future outcomes. The predictive ability of ARDEEM was evaluated by:

- *Backcasting*. The model was backcast[272] so as to produce results for the period 1980 to 1998. Graphs of key variables (*Population*, *Capital*, *Commodity Use*, *Commodity Supply*, capital investment, labour force participation, employment and so on) were plotted against actuals. Given the use of time series regression to 'curve fit' historical trends, it is perhaps not surprising that the results generated reflected actuals.
- *Comparison with Statistics New Zealand projections*. In the case of the Population, births, deaths, net migration and labour force variables it was possible to compare ARDEEM simulation results, under a Business as Usual Scenario, with SNZ projections.

Overall, it is important to remember that complete validation of a model by comparison with the real world is not possible, as ARDEEM only captures a selected number of components and behaves purely in response to its internal relationships.

11.10 Scenario Analysis

There are several reasons why policy and decision makers need to look into the future. This includes planning for possible futures, deciding between competing alternatives, making provisions for new infrastructure, and so on. Underpinning all of these reasons is arguably a desire to manage complexity and minimise risk (Shearer, 1994). While it is impossible for us to predict the future, it is however useful for us to understand what 'might' happen in the future. This forces us to consider the implications of our proposed trajectories; reducing uncertainty

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[272] Several simulations were required for this purpose; with appropriate corrections to the conceptualisation of ARDEEM being made following each simulation.

and avoiding possible pitfalls. Scenario modelling is one approach that may be used to help us simulate possible futures and their implications (Wilson, 1978; Schwarz, 1987).[273]

Scenarios have been defined by Kahn and Wiener (1967) as "a hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points" (Wilson, 1978, p. 225). SRI/CSSP (1975), Boshier *et al.* (1986) and Schaar (1987) have identified several key advantages of the scenario approach, including: (1) suitable for long-run projections where uncertainty is high and historical relationships have been characterised by dynamic feedbacks, non-linearities, time lags and the like; (2) help us to see the future in totality, rather than piecemeal; (3) allows us to trace people's behaviour in the face of perturbation; and (4) may provide common ground for communication between diverse interest groups or backgrounds.

Scenario development has several important methodological considerations, including: (1) how many scenarios? Despite the lack of agreement within the literature, there seems to be a consensus for three scenarios (Linneman and Klein, 1979). Two scenarios are likely to be categorised as 'good and bad', while the simulation of more than three scenarios often becomes uncontrollable; (2) what time horizon? Most analysts agree that scenario analysis is best suited for long-run simulation (Wilson, 1978; Schnaars, 1987; Armstrong, 1978; Linneman and Klein, 1979; van der Heijden, 1996) and (3) what is the process for constructing and writing scenarios? The development of consistent and comprehensive scenarios typically involves the following steps (Wilson, 1978; van der Heijden, 1996):

- *Step 1: Selection of scenario themes.* This will involve consideration of possible future changes in cause and effect, development of internal consistency, avoidance of contradictory sub-themes, and relevance to the issues facing the client or stakeholders most interested in the simulation.
- *Step 2: Carefully detailed, plausible and informative story lines.* The story line should ideally be formulated in the form of a qualitative and contextual narrative, and be underpinned by careful documented assumptions that ensure diversity and generate plausible and rich scenarios. A central tenet of story writing is the development of a 'gestalt' or integrated narrative, rather than a disintegrated or piecemeal one.
- *Step 3: Setting of initial driver values.* All initial values should be carefully specified as it is these values which are the main determinants of each scenario.

[273] Forecasting is the major alternative approach. It is typically quantitative, relying on historical trends in key system variables to project futures. It is often undertaken with only limited understanding of how a system operates; particularly the consequences of dynamic feedbacks between key system variables. For this reason forecasting is better suited to projecting short-or-medium term futures.

- *Step 4: Simulation and generation of indicator variables for each scenario.* These indicators should encompass variables that may be used to assess (1) the validity of the model's structures and behaviours (refer to Section 11.9), and (2) the modelling results. Under ideal circumstances interest and stakeholder groups should be involved in assessing the modelling results. Their opinions, views and inputs are useful in evaluating model results. Refinements may include rewriting of the narrative, resetting of driver values, development or redevelopment of indicators, and improvements to the model's internal structure.
- *Step 5: Reporting of results.* This includes presenting results to clients and stakeholder groups, and also often analysing the possible policy/investment implications of each scenario. Comparison of the scenarios is critical as this provides insight into the strengths, weaknesses and tradeoffs of each scenario. This will aid decision makers in selecting the best, or most appropriate, actions given the scenario results.

11.10.1 ARDEEM Scenarios

Three scenarios are developed for ARDEEM below. These scenarios are developed to demonstrate the usefulness of ARDEEM, but require signficiant further work – in particular, further peer review and, in turn, redevelopment.[274]

- *Scenario 1: Business As Usual(BAU).* The 'business as usual' scenario assumes that the trends experienced over the last 10 to 20 years will continue to prevail over the next 50 years. These trends are captured in the regression equations used throughout this Chapter to initialise ARDEEM's exogenous variables. Given that these trends are discussed in depth in earlier sections of this Chapter no further discussion is presented here.
- *Scenario 2: Cornucopian Growth(CG).* Under the cornucopian growth scenario market orthodoxy holds sway. This is a world where the ideology of economic rationalism, liberalism and consumption hold a monopoly of power. Key features of the scenario are (1) an increased instensification of economic interdependence with other economies, and (2) a desire for increased levels of material wealth. Resource constraints are disputed because technological substitutes are readily available.

[274] To this end a series of workshops is scheduled under the Sustainable Pathways FRST contract. These workshops will focus on 'what makes Auckland tick' from the viewpoint of key actors within the Auckland Region, namely: central and local government politicians, central and local government policy makers, infrastructure provides, developers, iwi, business and the public at large. These workshops will be jointly prepared and presented by the author and Professor Richard Le Heron of the School of Geography and Environmental Science, University of Auckland.

- *Scenario 3: Prudent Pessimism(PP).* Aucklanders adopt a communal philosophy of self-sufficiency. Global geopolitical instability and cultural social change override the incentives of economic globalisation. Aucklanders develop a strong and mutual sense of purpose including a shared national desire for sustainable living. Underpinning this desire is the belief that current material consumption cannot be sustained without future implications i.e. conservation and maintenance of critical natural capital for future generations is seen as paramount.

The key exogenous drivers of change in the 'Cornucopian Growth' and 'Prudent Pessimism' scenarios are specified in full in Table 11.1 below.

Table 11.1 Summary of Drivers under Each Scenario

	Cornucopian Growth	Prudent Pessimism
Fertility rate	Woman defer having children until their mid 30's, focusing instead on gaining material wealth. Fertility rates for under 29 year olds are 0.03 percent below the BAU scenario, while fertility rates for over 30's increase marginally at 0.01 percent above the BAU scenario.	Past fertility trends prevail for woman under 30 years of age. A marginal decrease in fertility rates (0.01 percent below the equivalent BAU rate) occurs for woman over 30; a consequence of lower material wealth.
Mortality rates	Reflect past trends.	Reflect past trends.
Net migration	Growth in the economy necessitates skilled and semi-skilled employment opportunities which cannot be fullfilled locally. A more open immigration policy is therefore pursued to avoid possible skill shortages. Net migration numbers grow at 12.5 percent above the BAU scenario.	A very tight immigration policy is adopted in an attempt to avoid overexploitation of the nation's natural resources. Immigrants are selected that have skills which will make New Zealand more self-sufficient. Overall, the number of immigrants drops at a rate 5 percent below the BAU scenario.
Labour force participation	Reflect past trends, except for those aged over 60 who engage at a rate 2.5 percent above the BAU scenario; a consequence of a desire for higher levels of material wealth.	Reflect past trends, except for those over 60 who engage at a rate 0.5 percent above the BAU scenario. This is a result of a desire to retain skilled labour as long as possible in the workforce.
Unemployment rates	Reflect past trends.	Reflect past trends.
Employment distribution by industry	The distribution of employment in the primary and secondary industries reflects past trends. More people are however involved in services; in particular retailing and wholesaling. Services thus grow at a rate 1 percent above the BAU scenario.	A trend toward a more self-sufficient economy requires that more people are employed in primary and secondary industries; at a rate 1.5 percent above the BAU scenario.
Investment rates	The desire for greater material wealth results in increased investment in manufacturing and service industries at a rate 1.5 percent above the BAU scenario.	Primary industry investment rates increase with the desire to be self-sufficient; this occurs at a rate 1 percent above the BAU scenario.
Depreciation rates	Reflect past trends.	Incentives are introduced by government to maintain high quality capital stocks for longer periods within the economy. This results in a depreciation rate 1 percent lower than the BAU scenario.
Technology rates	Technological solutions result in substantial increasing returns in all industries within the economy; at a rate 5 percent above the BAU scenario. Technology continues to offset environmental degradation.	Technological change is felt most in the primary industry at a rate of 5 percent above the BAU scenario, the secondary and tertiary industries however experience less technological innovation and cannot completely offset environmental degradation (growing at a rate 2.5 percent below the BAU scenario).
Substitution effects	Although the use of domestically supplied commodities reflects past trends, the desire for more luxurious commodities results in the substitution of domestically produced commodities for imported commodities. This occurs at a rate 2.5 percent above the BAU scenario.	Domestically supplied commodities are substituted for imported goods, respectively growing at 2 percent above and -3.5 percent below the BAU scenario. This is a response to a desire to minimise transportation costs to the environment to encourage local production of commonly consumed commodities.
International exports	All sectors grow exports at rate 1 percent above the BAU scenario.	There is movement away from international export as a result of the environmental implications of transportation; at a rate 1.5 percent below the BAU scenario.
Interregional exports	All sectors grow exports at rate 1 percent above the BAU scenario.	Interregional exports grow at a rate of 2 percent above the BAU scenario.
Eco-efficiency improvements	Little regard is given to improving the eco-efficiency of commodities. Consequently, eco-efficiency improvements decline at a rate 1 percent below the BAU scenario.	Conservation and maintenance of natural capital is pursued both in relation to commodities consumed within the economy, extracted directly from the environment or released back into the environment after use. Overall, eco-efficiency rates vary between 1 and 3 percent above the BAU scenario.

Note: All rates are annualised geometric averages for the 2001 to 2051 period.

11.10.2 Simulation Results

The results presented in this Section are preliminary and are meant only to illustrate the potential value of ARDEEM.

There is very little difference between the three scenarios for growth in total population (Figure 11.8a) and total employment (Figure 11.8b) between 2001 and 2051. Under the Cornucopian Growth (CG) scenario, population is projected to grow to only 100,000 or so higher than under the Business As Usual (BAU) and Prudent Pessimism (PP) scenarios. There is overall steady population growth from around 1.2 million in 2001 to about 2 million by 2051 for all three scenarios. Total employment (FTEs) mirrors population growth, with minor differences between the three scenarios. Overall growth in total employment is projected at about 400,000 FTEs between 2001 and 2051. Productivity gains are evident however in projected total output per worker (Figure 11.8c), with output tripling under the CG to $450,000 in 2051, one and a half times more than under the BAU, and three times more than under PP. PP shows only a 40 percent growth in total output per worker over 50 years, while CG indicates a 200 percent growth over the same period. Total capital per worker (Figure 11.8d) shows an initial decline under all three scenarios. This decline occurs because capital investment rates were being outstripped by capital depreciation rates. Under CG, total capital per worker begins an upward trend around 2013 while under PP this only occurs 30 years later, around 2033. Under CG this variable grows rapidly to $650,000 per worker (an 85 percent increase between 2001 and 2051), while BAU shows a growth of about 25 percent. There is an overall decrease of about 20 percent under PP over the study period with the variable not recovering its 2001 level by 2051.

Under CG, total industry output (Figure 11.8e) escalates fairly rapidly to nearly five times its 2001 value over the study period, with a difference of about $200,000 million between CG and BAU at 2051. Under PP, total industry output grows relatively modestly, doubling over the 50 year study period. Total industry GDP (Figure 11.8f) mirrors total industry output, with CG 50 percent higher at $150,000 million, and PP 30 percent lower at $70,000 million, than BAU of $100,000 million at 2051. BAU total physical supply (Figure 11.8g) grows by 200 million t over the study period, while growth of $380 million t under CG makes it double that under PP at 2051. Similarly, total physical use (Figure 11.8h) grows by three and a half times under CG, but only doubles under PP in 50 years.

Under CG, total physical imports (Figure 11.8i) rapidly increases nearly threefold to 75 million t over the 50 year period, 35 million t and 45 million t higher than under BAU and PP respectively. Under all three scenarios, total physical exports and final demand (Figure 11.8j) shows relatively slower growth from about 70 million t in 2001 to between 120 million t (PP) and 170 million t (CG), i.e. a 70 to 140 percent increase. Similarly to total physical imports, CG shows total physical exports and final demand to be 35 million t higher than BAU at 2051. Under CG, total raw material inputs (Figure 11.8k) quadrupled, a requirement nearly 60 percent greater than BAU. In comparison, this variable under PP doubled over the 50 years. Similarly, total residual outputs under CG almost triples, while under PP it doubles from 2001 to 2051. Under CG, the economy produces nearly 40 percent more residual outputs (370,000 t) than BAU, and nearly 70 percent more than PP (220,000 t) by 2051.

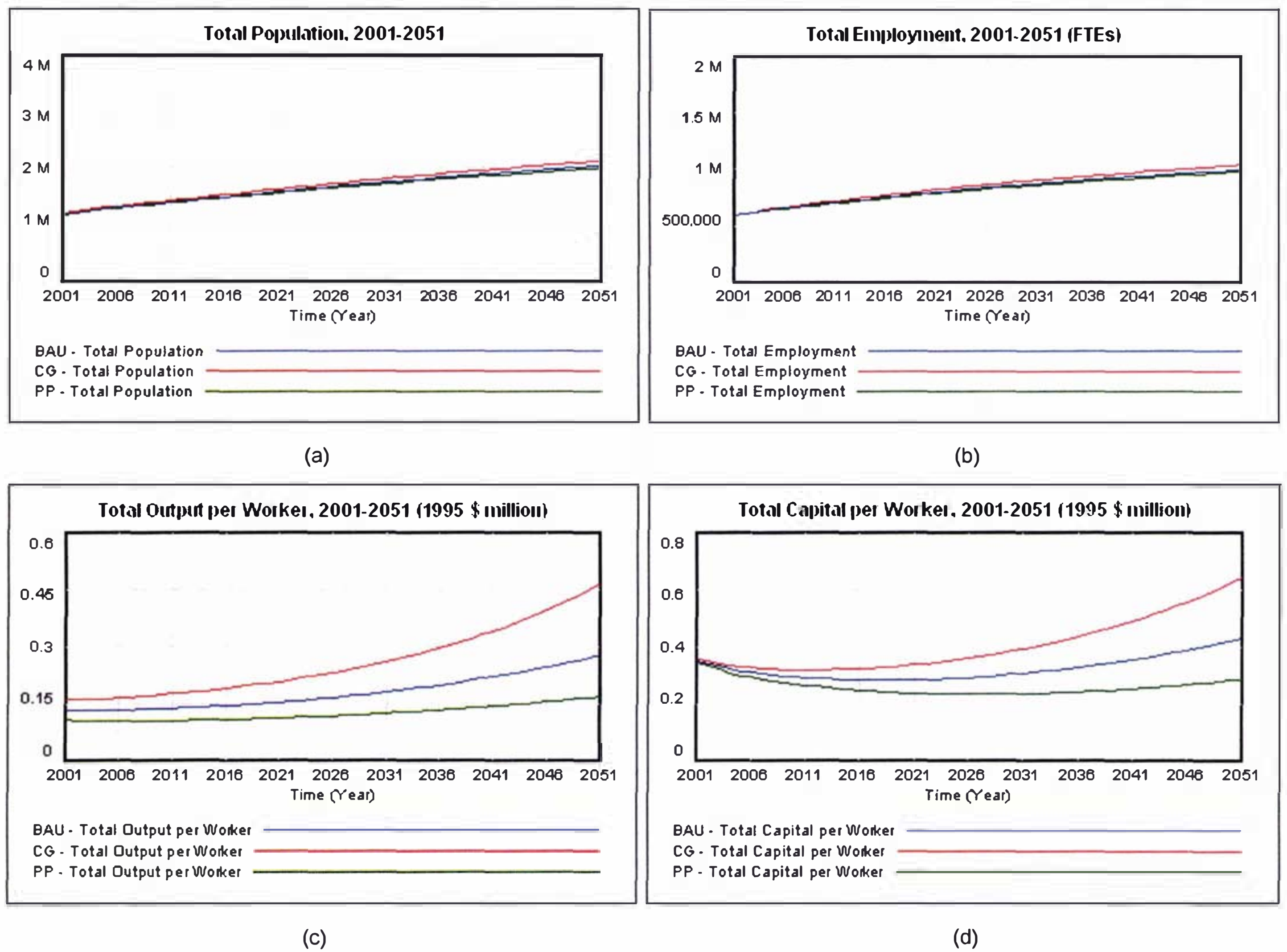
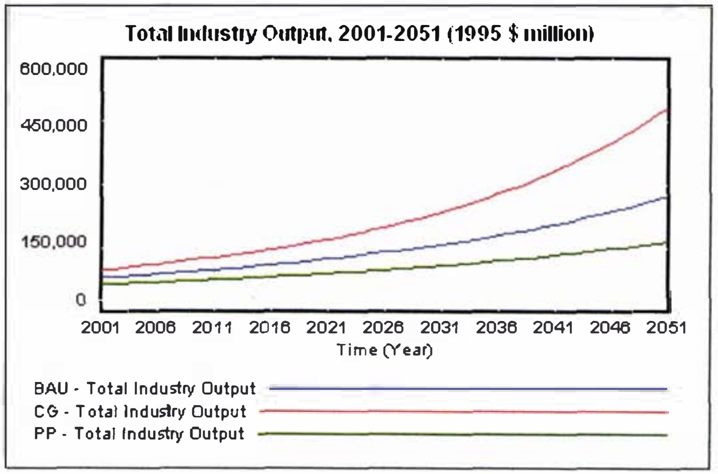
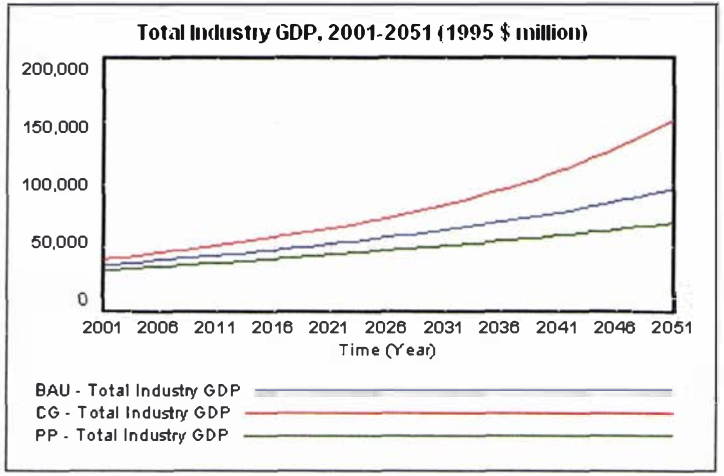


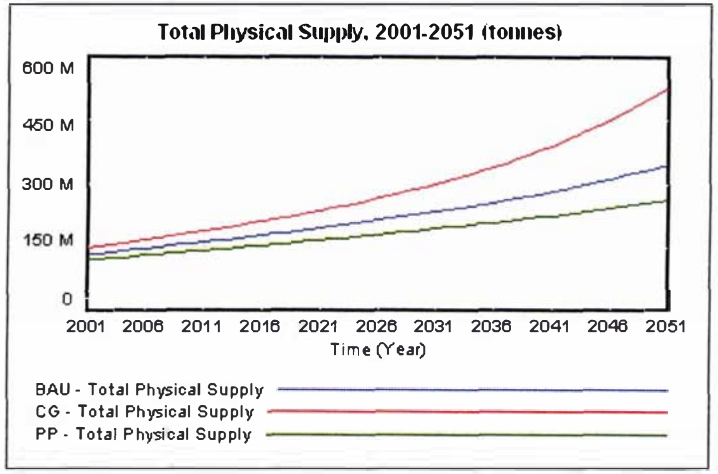
Figure 11.8 **ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism**



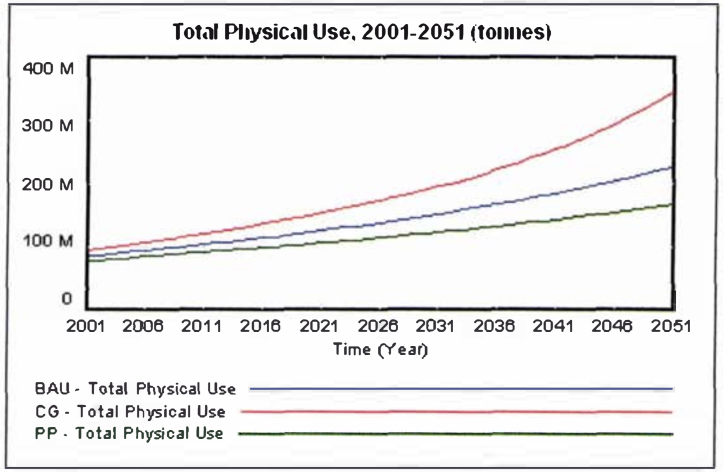
(e)



(f)



(g)



(h)

Figure 11.8 ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism (Continued)

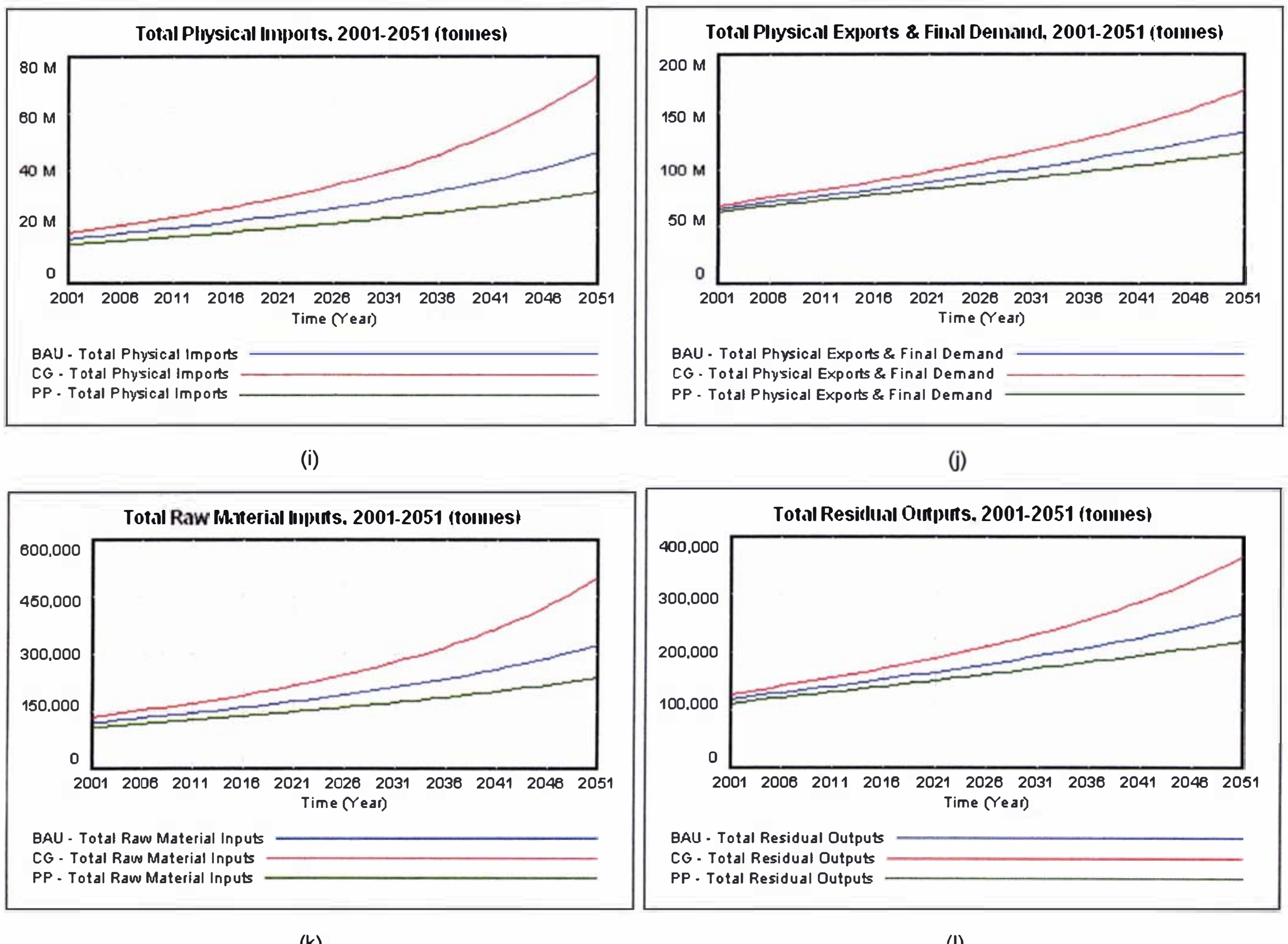


Figure 11.8 ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism (Continued)

11.11 Limitations of the ARDEEM

The ARDEEM, like all other mathematical models, is underpinned by a number of assumptions. Often the degree of influence of these assumptions depends on the worldview or belief system of the user analysing the modelling results. It is therefore possible that ARDEEM simulations may, in the eyes of different users, produce results ranging from totally plausible and likely, to completely implausible and unlikely. The purpose of ARDEEM is not however to predict futures, but instead through simulation to investigate the possible dynamic implications of change in the Auckland Region environment-economy system. ARDEEM's major limitations include:

- *Neglect of natural resource constraints and critical environmental processes.* A significant shortcoming of the model is the omission of possible diminishing returns associated with resource scarcity and the degradation of environmental processes. Both international and domestic resource scarcity/environmental degradation will effect the Region's economic growth. Modelling such consequences requires not only data for Auckland Region, but also for the globe. An attempt was made to construct a biogeochemical cycling model of Auckland Region; this however proved too difficult primarily due to data paucity. Nevertheless, a prototype model was constructed for the globe – refer to the Global Biogeochemical Cycling Model (GBCM) presented in Appendix B. This limitation is discussed further in Section 11.11.1 below.
- *Price and substitution effects.* The ARDEEM, like the *Limits to Growth* model, may be criticised for the lack of consideration of price effects which might lead to substitution between factor inputs. It is argued that if we know the price elasticity of a commodity then changes in the commodity's supply and demand may be predicted. The ARDEEM, like other simulation models, may only be used to investigate scenarios i.e. it cannot predict the future. It is however possible to test out a scenario with price change and substitution.
- *Number of industries and commodities.* The ARDEEM is currently only a prototype covering three industries and three commodities – a result of time constraints imposed on the completion of this thesis. Only minimal additional system dynamics modelling is however required to extend ARDEEM to, say, 20 or 30 industries, and in the case of commodities to, say, 200 plus commodities. Data constraints will however impose restrictions on industry/commodity coverage in future versions of ARDEEM.
- *Spatial dynamics.* Many of the sustainability issues facing Auckland Region are localised or spatially specific in nature and thus not suitable for simulation in ARDEEM. Consideration of the spatial dynamics is however beyond the scope of this

thesis. With further research it may however be possible to interface ARDEEM with static spatial models already in existence e.g. Auckland Regional Council's Auckland Strategic Planning (ASP) and Auckland Regional Transport (ART) models.[275]

11.11.1 Extending ARDEEM to Include Ecological Processes

The original intention was to build a module of ARDEEM that dynamically modelled the ecological processes in the Auckland Region, building on the static model outlined in Chapter 7 and the growth theory including natural resources developed at the end of Chapter 10. Although this could not be achieved within the time constraints of this thesis, a Global Biogeochemical Cycling Model (GCBM) was constructed which is broadly indicative of the type of model that could be developed.

The GCBM consists of (1) 73 'marker element' flows grouped according to the carbon, sulphur, nitrogen, phosphorus, and hydrological cycles, (2) 42 'non-marker element' flows, (3) 21 biogeochemical stocks broadly categorised into atmosphere, terrestrial biosphere, marine biosphere, hydrosphere and lithosphere, and (4) converters that govern the flow of the marker elements out of donor stocks. Initial runs of this global model indicated that the model could reliably simulate a number of anthropogenic perturbations, moving typically to new steady-state values.

The establishment of an Auckland Region model would require consideration of a number of additional factors, which time constraints did not permit. Firstly, the global model was based on a closed system, whereas the Auckland Region system is clearly an open system. For example, global emissions of CO_2 will affect ecological processes in Auckland Region due to the inflow of CO_2 emissions from elsewhere in the world. This openness of the Auckland Region environmental system, particularly for atmospheric processes, is difficult to model due to both data and methodological issues that need to be addressed. Secondly, there is very little reliable data on the nature and extent of biogeochemical processes in the Auckland Region. Very indicative flow data was produced in Chapter 7, but this is inadequate for a dynamic model. Stock data is particularly difficult to obtain. It is estimated that it would take several person years to reliably estimate such data for the Auckland Region. Thirdly, as noted in Chapter 7, there are spatial effects that are important in modelling ecological processes in Auckland Region. The operationalisation of the global model assumed that for each process the spatial

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[275] This possibility is currently being explored under the Sustainable Pathways (MAUX) FoRST contract. Moreover, the final two years of this contract (i.e. 2008 and 2009) will be directed at developing a spatially explicit version of ARDEEM.

effects are irrelevant. For a regional system, such as Auckland Region, this isn't the case. For example, point source pollutants at relatively low levels of total emission, have highly localised effects. The same amount of total emissions spread across a larger area, may have little or no effect because of relatively low concentrations which fall below a biological threshold.

Chapter Twelve

Thesis Summary and Conclusions

This thesis has focused on the integration of economics and ecology in the study of Auckland Region's sustainable development. This integration has been demonstrated not only through the extension of several existing methodologies, and the creation and implementation of new methodologies, but also by critically analysing the underpinning theory concerning sustainable urban development. The purpose of this Chapter is to: (1) explicitly identify the key contribution of this thesis, in particular, how these contributions extend the body of knowledge beyond that which previously existed; and (2) identify areas for further research and development.

12.1 Thesis Contributions

The key contribution of this thesis has been the integration of economics and ecology in the study of Auckland Region's progress toward sustainable development. Underpinning this integration has been the adoption of a *systems framework* which has considered not only critical interdependencies occurring within the Auckland Region economy, but across the economy-environment interface and within the natural environment itself. These interdependencies have been studied through a variety of theories (e.g. urban and urban sustainability perspectives), static modelling (e.g. monetary input-output models, physical input-output models, lifecycle assessment, ecological footprinting, materials flow analysis, ecosystem service valuation) and dynamic models (e.g. the ARDEEM and GBCM system dynamics models) lenses. The major theoretical, methodological and empirical contributions of the thesis are considered below.

12.1.1 Theoretical Contributions

The theoretical dimensions of the question of urban sustainability and growth formed a critical core of this thesis, and the basis for the modelling that followed. The main theoretical contributions of this thesis are:

- *Establishment of a set of key theoretical principles for sustainable development for an integrated environment-economy system.* These principles were developed through a comprehensive critique of economic, ecological and thermodynamic interpretations of sustainability theory, and they integrate these various interpretations.

- *Critical analysis of the major theoretical approaches to urban development and sustainability.* Based on an environmental sociology viewpoint, the thesis consolidates the major schools of thought regarding urban development and sustainability. This work extends the earlier contributions of sociologists such as Catton and Dunlap (1978) by: (1) focusing purely on the urban system, and (2) incorporating theory about cities as ecosystems into the emerging, but currently underdeveloped, NEP perspective. Cities, like other ecosystems, function through the metabolism of mass and energy. This involves complex dynamics typified by time lags, feedbacks, and exchanges with other systems, and is regulated by biophysical constraints (e.g. the laws of thermodynamics).
- *Critical analysis of growth theory as applied to sustainability.* The main domains of growth theory as developed in economics are critically surveyed, and their applicability to the issue of modelling sustainability options in Auckland Region is examined. The salient features of growth theory are revealed and it is argued that much of the research effort conducted to date has proceeded without any consideration of biophysical or thermodynamic constraints. When these concerns are addressed, growth models exhibit diminishing returns to labour and capital, although (within biophysical limits) technological progress has potential to offset these effects.

12.1.2 Methodological Contributions

A major contribution of this thesis has been the development of methodologies and associated operational tools for analysing Auckland Region's economy-environment interactions. Moreover, these methods can be applied elsewhere. These methodological contributions are:

- *Methodology for the generation of regional commodity-by-industry monetary input-output models*: Typically, national industry-by-industry matrices are used to generate counterpart regional matrices. The development of methodologies for regionalising commodity-by-commodity matrices is a recent development led by the theoretical work of Jackson (1998) and Lahr (2001). This thesis extends this pioneering work by (1) establishing a detailed methodological sequence for generating commodity-by-industry input-output matrices, and (2) moving from theory to implementation. Several of the steps within this sequence introduce novel techniques for regionalising components of the commodity-by-industry framework such as value added, final demand and in table balancing. A feature of the sequence is that it allows superior data to be incorporated. Given that the methodology adopts internationally recognised statistical classifications (i.e. for industries and commodities) it could easily be replicated in other nations and regions.

- *Methodology for the generation and regionalisation of commodity-by-industry physical input-output models*: In Chapter 6, an innovative methodology for generating not only national, but also *regional* physical commodity-by-industry input-output models. So far, physical input-output tables have been constructed by only a few statistical agencies. This thesis establishes a detailed methodological sequence for constructing national and regional physical commodity-by-industry input-output models. The methodology, like that developed above, allows superior data to be incorporated, ensuring that the unique characteristics of a nation or region are accounted for. The adoption of internationally recognised classification systems and datasets (e.g. harmonised system) promotes easy replication of the methodology in other nations and regions.
- *Cumulative effects indicator as a measure of eco-efficiency.* This indicator, presented in Chapter 6, compares the total economic impact (benefit) to the total environmental impact (cost) of industries in the economy. Specifically, for a given industry it measures the Type I economic multiplier in relation to the ecological multiplier.
- *Methodology for measuring the dependence of economic industries on ecosystem services.* This method specifically links ecosystem service values ($) to sectoral activity in the economy. This enables, by input-output analysis, the: (1) calculation of the embodied ecosystem services ($) for various sectoral outputs, (2) explicit depiction of these embodied (direct and indirect) ecosystem service inputs into each industry in the economy, using tree diagrams. This leads to an important understanding of how each industry in the economy directly and indirectly depends on ecosystem services. This dependence is illustrated for two service industries, namely: air transport, services to transport and storage [35] and business services [42]. Such industries, although apparently far removed from ecosystem services, do actually critically depend on ecosystem services.
- *Methodology for the calculation of regional ecological footprints and interdependencies using input-output analysis.* This methodology, presented in Chapter 8, extends the earlier work of Bicknell *et al.* (1998) to calculate ecological footprints *at a sub-national level and to show how different regions ecologically depend on each other.* The method focuses on land and energy embodied in interregional trade, because it is argued that it is not only the magnitude of the ecological footprint that matters, but also the impact (or sustainable management practices) at the location of origin. This methodology was published in *Ecological Economics*, 2004, Volume 50, pp.49-67.
- *Operationalisation of a dynamic environmental-economic simulation model of an urban system.* To the author's knowledge, this is one of the first dynamic models to be developed for an urban region that allows the environmental consequences of economic

change to be investigated directly. The model incorporates several unique contributions: (1) it endogenises the cause-effect chains underpinning several key factors of production (e.g. employment, commodity use and importation)[276], (2) it captures the complex monetary and physical interdependencies between industries in terms of supply and use of commodities by adopting a commodity-by-industry input-output framework for its economic module[277], and (3) it captures in physical terms the raw material inputs, and residual outputs, flowing across the Auckland Region environment-economy interface. This model was shown to be a powerful and robust tool for analysing urban sustainability issues, as illustrated by the scenario analysis.

- *Construction and operationalisation of a dynamic biogeochemical cycling model for the globe.* This model was successful constructed for the globe (refer to Appendix B), because the original intention of building such a model for the Auckland Region proved too difficult (refer to Section 11.12) mainly due to lack of data. This global model, for the first time, comprehensively integrates the C, H, P, S and N cycles. Although more detailed models have been developed for individual cycles, only a few (e.g. Mackenzie *et al.* (1993), den Elzen *et al.* (1995)) models have attempted to integrate the biogeochemical cycles, but not as comprehensively as the model presented in Appendix B. The complexity of the model arises from the numerous feedbacks between the biogeochemical cycles, rather than in sub-components of each cycle. It captures not only the major elemental fluxes of each process, but also all of its by-products and their associated feedbacks. Initial runs of this global model show the model to be robust returning to a steady-state after an initial perturbation.

12.1.3 Empirical and Knowledge Contributions

This thesis has involved producing large multi-dimensional data sets that have led to improved knowledge and insight into the nature of the Auckland Region economy and its interrelationship with the biophysical environment:

- *Physical Input Output Model of Urban Metabolism.* Previous studies have analysed and produced some data on the urban metabolism of cities, e.g. Newcombe's study of Hong

[276] An attempt is made in Appendix L to endogenise technological change by capturing the dynamics of idea creation and formulation; although operational, only hypothetical data exists to simulate its implications.

[277] Ryan (1995) has also utilised input-output analysis in dynamic simulation. His model, however, adopts an industry-by-industry rather than commodity-by-industry input-output framework for analysing economic interdependencies. As industry-by-industry models assume a single homogeneous output per industry (i.e. no joint production), the number of commodities in Ryan's (1995) model must equate to the number of industries. By comparison, ARDEEM may be restricted to, say, 30 industries, but can analyse hundreds, or even thousands, of commodities.

Kong. These studies however have been at a very aggregative level, generating few data and little information about the flows of energy and materials within the economy and across the economy-environment boundary. This thesis, for the first time, produces a detailed data-rich picture of the urban metabolism of a city, by using the Physical Input Output Table (PIOT) approach. In 1997-98, the material input into the Auckland Region economy was 128,674 kt (raw materials 111,793 kt, imports 15,082 kt, residual inputs 1,799 kt). Most of this material input was destined to be residual outputs into the environment (109,789 kt), with very little recycling or re-use. The PIOT also quantified these physical inputs and outputs into each of the industries (48) in the Auckland Region economy.

- *Auckland Region's Dependence on Ecosystem Services and Processes.* The thesis used two separate but related analyses to quantify how the economy critically depends on ecosystem service inputs. Firstly, a preliminary quantitative picture of the main ecological processes (through input-output matrices) was generated. Secondly, the ecosystem services input ($) was quantified to be $1.03 billion, compared with a regional GDP of $33.2 billion for 1997-98; although it must be remembered that this included only the terrestrial ecosystem services inputs within the Auckland regional boundary. Households was the largest direct appropriator of ecosystem services at $241 million, followed by livestock and cropping ($201 million), water supply ($189 million), mining and quarrying ($135 million) and dairy cattle farming ($134 million). Service sectors however become more significant when indirect inputs of ecosystems are included in the analysis (refer to Chapter 7).
- *Ecological Footprint of the Auckland Region.* It was found that Auckland Region had the largest ecological footprint (2,300,000 ha), in excess of 1.3 times that of Canterbury, the next largest region. Auckland (2.00 ha per person) along with Wellington (2.40 ha per person) and Nelson (1.86 ha per person) have the largest per capita footprints in New Zealand. These are the three most urban regions and this seems to be the main determinant of their low footprints. More importantly, this footprint analysis also highlights the ecological dependency of Auckland Region on other regions in New Zealand (particularly the Waikato, Northland and Otago), as well as on other countries through international trade. That is, Auckland Region is a significant net importer of embodied land (1,420,000 ha). Most of Auckland Region's footprint was appropriated by the manufacturing sector (48.6 percent), followed by the household sector (24.2 percent), service sector (15.9 percent) and the agricultural sector (7.2 percent)
- *Eco-Efficiency of Industries in the Auckland Region Economy.* Valuable information and insights about the eco-efficiency of 48 industries in the Auckland Region economy were generated by the multiplier analysis in Chapter 6. Many industries could be

evaluated in terms of the embodied resources (or pollutants)[278] they require (or generated) to produce one unit ($) of output. Some industries, for example, showed that they had large multipliers (low eco-efficiency) for energy and associated air emissions – e.g. paper and paper products [16], non-metallic mineral products [20], and basic metal manufacturing [21]. Other industries had large methane emissions multipliers – e.g. the land based industries including livestock and cropping [2], dairy cattle farming [3] and other farming [4], as well as those associated with the downstream processing of land based products, including meat and meat products [10] and dairy product manufacturing [11].

12.2 Limitations and Future Research

As outlined in the relevant Chapters, several limitations could be addressed in future extensions of this research. These are discussed below.

12.2.1 Theoretical Analysis

The theory underpinning the concept of urban sustainability is still not well developed and lacks integration across various disciplinary based schools of thought. As is argued in Chapter 3, a research agenda for building and maturing the New Environmental Paradigm approach to urban sustainability could include:

- *New ecological ideas and terms.* Development of specific ecological ideas uniquely applicable to cities and urban spaces. There is a tendency to draw ideas and analogies directly from biological ecology and apply them to cities. At the very least, applying ideas such as carrying capacity to urban situations should be undertaken with care;
- *Stronger links between HEP and NEP research.* Forging stronger links between the established HEP research and the more recent NEP thinking. For example, few studies , with the exception of Huang (1998), attempt to explain the ecological determinants of urban phenomena (e.g. spatial zonation) that have long been observed in the HEP literature. The two schools of thought most often operate in complete isolation of each other; and
- *Institutionalisation.* Institutionalising the NEP view of urban sustainability and building a critical mass of research activity in this area. Institutionally the NEP-based field of

[278] Other resources covered in the ecological multiplier analysis include land and water inputs. Pollutants include carbon dioxide, nitrous oxide, methane, biological oxygen demand, phosphorus, total kjeldahl nitrogen and solid wastes.

urban sustainability is weak, with no strong international community of scholars or teaching institutions. HEP scholars from the social sciences dominate the field, while NEP scholars in urban areas are often marginalised.

The issue of growth theory and how to adjust it to incorporate ecological and thermodynamic constraints is even more problematic. Most growth theory is predicated on assumptions of technological optimism and neglects ecological processes or consequences. Mackenzie *et al.* (1993), den Elzen *et al.* (1995), and Ayres (2001, 2005) *inter alia* are some of the few analysts to acknowledge biophysical constraints when considering growth theory. Future research agendas must critically examine the HEP assumptions of such growth theory, and propose alternative theoretical frameworks which are more appropriate for analysing urban sustainability.

A broad level theoretical concern is the lack of scholarly enquiry into the connections between the critical theoretical elements identified in this thesis; e.g. sustainability theory, urban theory and growth theory. Theorists tend to specialise, with little or no knowledge of, or interest in, other theoretical areas. Few (if any) theoretical enquiries truly integrates these theoretical elements, but this integration is needed urgently if we are to develop a body of theory that enhances the holistic understanding of urban sustainability.

12.2.2 Static Systems Analysis

The static systems analysis of Auckland Region environment-economy interactions is a strength of this thesis because it is comprehensive, and has produced high quality of data. Nevertheless, some areas could be developed by future research.

- *Chapter 5 – Economic Input-Output Model.* The regionalisation process makes some assumptions that lead to imprecise calculation of the commodity-by-industry model of Auckland Region. Future research could be focus either on improving the method (thus alleviating the need to make these assumptions) or on collecting superior data to replace the assumptions. Areas needing attention are: cross hauling (only net flows are considered), self sufficiency (the regionalisation method assumes maximum self-sufficiency in economic production), the technology assumption (the regionalisation method assumes the region has the same mix of technologies as the nation), and consumption patterns (the method assumes the same consumption patterns occur in the region as the nation).

- *Chapter 6 – Physical Input-Output Model.* The PIOT was constructed using mainly estimated data. Several consequent limitations could be addressed by further research. These limitations include: (1) the export and import price data do not take account of import and export exclusions, coding errors and quality improvements; (2) estimated national (rather than actual regional) price data are used to convert value ($) data to physical data in the regional PIOT, but actual regional price data would better estimate the regional PIOT; and (3) the economic input-output model (from Chapter 5) was a starting point only and, as mentioned above, this could be improved.
- *Chapter 7 – Input-Output Model of Ecological Processes.* This model could be substantially improved, as the data presented in Chapter 7 are only broadly indicative. Shortcomings and improvements include: (1) the model currently only records fluxes within the region, but future development should focus on 'cross boundary' flows; (2) all data in the model are estimated from scaled down global data. Actual data for the Auckland Region should be collected and synthesised into the model, or modelled data based on knowledge of regional processes and system attributes should be used, following the type of approach used by Costanza *et al.* (1973) for the Mississippi Deltaic Plain Region; and (3) future research should attempt to connect the flows in the ecological input-output model to the models of the economy presented in Chapters 5 and 6.
- *Chapter 8 – Ecological Footprint Analysis.* This analysis is considered robust and needs little improvement. However, future development could focus on land productivity (quality) differences in the appropriated land, and on extending the ecological footprint to include resources other than land, and other pollutants other than carbon dioxide.

12.2.3 Dynamic Systems Analysis

The ARDEEM is a tool aimed not at predicting futures, but at understanding how feedbacks, non-linearities and time lags may influence key system variables, and through simulation investigating the possible dynamic implications of change in the Auckland Region environment-economy system. This should be borne in mind while considering ARDEEM's primary limitations and opportunities for development:

- *Price and substitution effects.* The ARDEEM, like the Limits to Growth model, may be criticised for not considering price effects which might lead to substitution between factor inputs. If we know the price elasticity of a commodity then changes in the commodity's supply and demand may be predicted. The ARDEEM, like other simulation models, may only be used to investigate scenarios i.e. it cannot predict the future. It is however possible to test a scenario with price changes and substitutions.

- *Neglect of critical environmental processes.* A significant weakness of the model is that it neglects the critical life supporting biogeochemical processes of the environment. These processes provide humans with resources, waste assimilation, opportunities for spiritual fulfilment, scientific learning and so on. Therefore, any environmental-economic model which does not consider their influence is incomplete.
- *Number of industries and commodities.* The ARDEEM is currently only a prototype covering three industries and three commodities. This is a consequence of time constraints imposed on the completion of this thesis. However, only minimal additional system dynamics modelling is required however to extend ARDEEM to, say, 20-30 industries, and for commodities to, say, 200 or more commodities.
- *Spatial dynamics.* Many sustainability issues facing Auckland Region are localised or spatially specific and thus not suitable for simulation in ARDEEM. Consideration of these spatial dynamics is beyond the scope of this thesis; nevertheless, further research may enable ARDEEM to interface with existing static spatial models e.g. Auckland Regional Council's Auckland Strategic Planning (ASP) and Auckland Regional Transport (ART) models.

List of PhD Outputs

During the course of this research four papers were accepted for publication in journals (lead author in two cases, analytical support in two cases), two papers are manuscripts in progress (one lead author, one secondary author), three papers were presented at conferences, one book chapter was accepted for publication (principal modeller), two refereed reports were published (one lead author, one analytical support), and nine unpublished reports were written for various commercial clients. All of these research outputs build on methodologies created in this thesis, and to a lesser extent, report its key findings. The emphasis of these outputs is not however solely on Auckland Region, but instead on the nation, other regions and specific economic industries. The full list of outputs is presented below:

Papers

Published Papers

McDonald, G.W. & Patterson, M.G. (2004). Ecological Footprints and Interdependencies of New Zealand Regions. *Ecological Economics, 50*: 49-67.

Jollands, N.A., Golubiewski, N.E. & McDonald, G.W. (2005). Implications of Changing Employment Patterns on Urban Ecosystem Service Requirements. *The International Journal of Environment, Workplace and Employment*, *3-4*: 310-335.

Papers Accepted for Publication

McDonald, G.W., Forgie, V.E., & MacGregor, C. (In press). Treading Lightly: Ecofootprints of New Zealand's Ageing Nation. *Ecological Economics.*

Jollands, N.A., Golubiewski, N.E. & McDonald, G.W. (In press). Linking Policy and Science: A Study of Metro Christchurch Ecosystem Service Appropriation. *The International Journal of Environment, Workplace and Employment.*

Forthcoming Papers – written, but not yet submitted for publication

McDonald, G.W., & Le Heron, R. (2005). *Changes in the Clusters of Comparative Advantage in the Auckland Region Economy 1986-2001.* Manuscript in progress.

McDonald, G.W., Le Heron, R.B., & Patterson, M.G. (2005). *Canterbury's 'Hidden' Economy: Assessing the Value of the Region's Ecosystem Services.* Manuscript in progress.

Patterson, M.G. & McDonald, G.W. (2005). *Regional Level Environmental Accounting in New Zealand: EcoLink and Other End-User Led Initiatives.* Manuscript in progress.

Conference Papers

McDonald, G.W. & Patterson, M.G. (2000). Ecological Footprints and the Interdependencies of New Zealand Regions. International Society of Ecological Economics. Presented at People and Nature: Operationalising Ecological Economics, 5 – 8 July, 2000, The Australian National University, Canberra, Australia.

McDonald, G.W. (2003). Treading Lightly: Recent Ecological Footprint Work in New Zealand. New Zealand Centre of Ecological Economics. Presented at Ecological Economics at the Cutting Edge, November 16, 2003, Auckland, New Zealand.

Flemmer, C.L., Flemmer, R.C., McDonald, G.W., Archer, R.H., & Cleland, D.J. (2005). An Assessment of the Ecological Impact of the New Zealand Dairy Farming Sector. Australia New Zealand Society for Ecological Economics. Ecological Economics in Action, 11 – 13 December, Massey University, Palmerston North, New Zealand.

Book Chapters

Patterson, M.G., G.W. McDonald, N.E. Golubiewski, V.E. Forgie & N.A. Jollands (2006), Climate change Impacts on Regional Development and Sustainability: An Analysis of New Zealand Regions. In M. Ruth (Ed.), *Smart Growth and Climate Change: Regional Development, Infrastructure and Adaptation (pp.82-108).* Edward Elgar Publishing Ltd.

Reports

Published (Refereed) Reports

McDonald, G.W. & Patterson, M.G. (2003). Ecological Footprints of New Zealand Regions. Environmental Reporting Technical Paper. Ministry for the Environment. Wellington, New Zealand. 162pp. ISBN 0-478-24085-6. Downloadable from: http://www.mfe.govt.nz/publications/ser/eco-footprint-sep03/eco-footprint-sep03.pdf

Patterson, M.G. & McDonald, G.W. (2004). How Clean and Green is New Zealand Tourism? Lifecycle and Future Environmental Impacts. Land Research Science Series No. 24. Lincoln: Manaaki Whenua Press, 141pp. ISBN 0-478-09359-4. Downloadable from http://www.mwpress.co.nz/store/viewItem.asp?idProduct=498

Unpublished Reports

McDonald, G.W. & Patterson, M.G. (2001). Ecological Footprint of the Waikato Region. Report for Environment Waikato. Auckland: McDermott Fairgray Group Ltd.

McDonald, G.W. (2003). Canterbury Region's Hidden Economy: Assessing the Value of the Region's Ecosystem Services and Biodiversity. Report for Christchurch City Council. Palmerston North: Landcare Research Ltd.

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McDonald, G.W. (2004). Ecological Footprint of Waitakere City Council. Report for Waitakere City Council. Takapuna: Market Economics Ltd.

McDonald, G.W. (2004). Conceptual Framework for a New Zealand Financial and Physical Input-Output Accounting System. FoRST Research Contracts MAUX0306 and WROX0305. Takapuna: Market Economics Ltd.

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APPENDICES

Appendix A

Input-Output Analysis: History, Mathematics and Assumptions

A.1 Brief History of Input-Output Modelling

The origins of input-output modelling may be traced back to the Physiocrats of the 18th Century. François Quesnay's *Tableau Economique* of 1758 traced successive rounds of wealth generated by agricultural expenditure. Although the *Tableau Economique* investigated the concepts of circular flow and general equilibrium, it was not until another Frenchman, Leon Walrus in his *Elements d'Economie Politique Pure* of 1874, that a detailed theoretical framework for analysing economic interdependence was created. Walras developed a theory of general equilibrium that utilised production coefficients to relate the quantities of factors required to produce a unit of product to levels of total production of that product. Contemporary input-output economics is attributed to Wassily Leontief, a Nobel prize-winning American economist, who in 1936 published an input-output table for the American economy. Leontief simplified the Walras model to develop a linear approximation based on the general equilibrium concept of economic interdependence (Miller and Blair, 1985).

A.2 Input-Output Tables

To construct an input-output table we must first develop the basic mathematics of input-output analysis. The structure of an industry's production process is represented by a vector of structural coefficients that describe the relationship between the inputs it consumes (i.e. purchases), and the outputs it produces (i.e. sales). Interdependence between industries is described by a set of linear equations expressing the balance between total input, and the aggregate output of each commodity and service produced (Leontief, 1985).

Thus, if an economy is separated into n industries, and if we denote X_i the total output (sales) of an industry i, and Y_i the final demand for industry i's production, then,

$$X_i = z_{i1} + z_{i2} + \ldots + z_{ij} + z_{in} + Y_i \qquad \text{(A.1)}$$

for $i = 1 \ldots n$, and $j = 1 \ldots n$.

The z terms represent inter-industry sales from industry i to industry j, and the Y_i term, sales to industry i's final demand (e.g. households, exports, capital formation and net increases in stocks). Taken together, the z terms and Y_i give the total output of industry i, X_i. We may then construct a system of equations for all n industries,

$$\begin{aligned}
X_1 &= z_{11} + z_{12} + \ldots + z_{1j} + \ldots + z_{1n} + Y_1 \\
X_2 &= z_{21} + z_{22} + \ldots + z_{2j} + \ldots + z_{2n} + Y_2 \\
&\vdots \\
X_i &= z_{i1} + z_{i2} + \ldots + z_{ij} + \ldots + z_{in} + Y_i \\
&\vdots \\
X_n &= z_{n1} + z_{n2} + \ldots + z_{nj} + \ldots + z_{nn} + Y_n
\end{aligned} \tag{A.2}$$

If we then consider the jth column of z's we have a column vector,

$$\begin{bmatrix} z_{1j} \\ z_{2j} \\ \vdots \\ z_{ij} \\ \vdots \\ z_{nj} \end{bmatrix} . \tag{A.3}$$

The elements of this vector represent the inputs (i.e. purchases) by industry j, including the purchases of intermediate demands and primary inputs (e.g. wages and salaries, imports, operating surplus, capital depreciation, subsidies and taxes). We now have the basis for the input-output model depicted in Figure A.1. An input-output model is conventionally presented in a matrix format with each industry assigned a row and column.[279] The element $\mathbf{z}_{ij}$ in row i, column j, represents the volume of goods flowing from industry i to be used as inputs in industry j. Primary data for populating the input-output model are typically obtained from national economic accounts, which are, in turn, derived from a nation's census of production or similar.

[279] This format is also commonly referred to as an 'industry-by-industry', 'institutional' or 'Leontief' input-output model.

	Industry 1	Industry ... *j* ...	Industry n	Sub-Total	House -holds	Govt. Expen-diture	Other Final Demand	Exports	Sub-Total	Total Gross Output
Industry 1 Industry ... *i* ... Industry n		Quadrant I z_{ij}				Quadrant II Y_i				X_i
Sub-Total										
Labour Operating Surplus Other Primary Inputs Imports		Quadrant III				Quadrant IV				
Sub-Total										
Total Gross Input		X_j								

Figure A.1 An Input-Output Table

An input-output table may be divided vertically into two parts: the part on the left represents the inputs into the production process of the productive industries, while the part on the right represents the sales to the final demand categories. Each of these parts may be further subdivided horizontally into two sections so as to distinguish between intermediate inputs and primary inputs. The resulting input-output table consists of quadrants (labelled I to IV in Figure A.1).

Quadrant I, known as the processing or intermediate demand quadrant, represents the flows of transactions between endogenous industries used in the intermediate stages of production. A key characteristic of the intermediate demand quadrant is that there must be the same number of rows as columns.

Quadrant II displays the sales by each industry to final demand i.e. the part of an industry's output not used by another industry as an input. It describes the consumer behaviour of a number of important markets including household consumption and exports. The column categories are known as exogenous as they are typically influenced by factors external to the economy.

Quadrant III describes the primary inputs used in each industry. These inputs are described as 'primary' because they do not form part of the output of intermediate production i.e. wages and salaries (representing labour), operating surplus, and imports. Summing the primary inputs, and in turn, subtracting imports, provides an estimate of the contribution made to GDP by each industry.

Quadrant IV displays the primary inputs that are directly used by final demand sectors. This includes non-market transfers such as benefits and pensions as well as imports of commodities for consumption by households and investors.

Embedded within the input-output model are several important accounting identities. Two of the most major are: (1) for each industry, $i=j$, total output, X_i, must equate to total input, X_j, and (2) the sum total of the final demand sectors must equate to the sum total of the primary inputs. Furthermore, the intimate relationship shared with national models enables standard economic aggregates such as Balance of Trade (i.e. exports less imports), and contribution to Gross Domestic Production by each industry to be evaluated.

A.3 Technical Coefficients

A critical assumption of input-output analysis is that the inter-industry flow from i to j depends entirely on industry j total output, X_j. Say, for example, an industry j sells computer keyboards; it is assumed that with any increase in the sales of keyboards, there will be a corresponding increase in sales of plastics, metals *etc.* required to create the keyboards. Based on this assumption a ratio of input to output may be formulated, commonly referred to as a technical coefficient. Thus, for a z_{ij}, the sale from row industry i to column industry j, and the total output of industry j, X_j, gives the technical coefficient a_{ij},

$$a_{ij} = \frac{z_{ij}}{X_j}. \tag{A.4}$$

Thus, the a_{ij}'s can be thought of as representing the first round inputs from each row industry i following a unit increase in output of any row industry i per unit of output produced by column industry j. The a_{ij}'s represent fixed relationships between an industry's output and its inputs. Moreover, the relationship is linear – hence, there are no economics or diseconomies of scale, only constant returns to scale. Equation A.2 may now be rewritten using the a_{ij}'s,

$$\begin{aligned}
X_1 &= a_{11}X_1 + a_{12}X_2 + \ldots + a_{1j}X_i + \ldots a_{1n}X_n + Y_1 \\
X_2 &= a_{21}X_1 + a_{22}X_2 + \ldots + a_{2j}X_i + \ldots a_{2n}X_n + Y_2 \\
&\vdots \\
X_i &= a_{i1}X_1 + a_{i2}X_2 + \ldots + a_{ij}X_i + \ldots a_{in}X_n + Y_i \\
&\vdots \\
X_n &= a_{n1}X_1 + a_{n2}X_2 + \ldots + a_{nj}X_i + \ldots a_{nn}X_n + Y_n.
\end{aligned} \tag{A.5}$$

A.4 The Leontief Inverse

A common question answered by input-output analysis, including at several points in this thesis, is: given a future projection of final demand, the Y_i's, how much output from each industry, the X_i's, would be required to meet the projection? This is a simple matter of solving a set of simultaneous equations where the Y_i's and a_{ij}'s are known, and the X_i's are unknown. In matrix terms, we define,

$$A = \begin{bmatrix} a_{11}a_{12} \cdots a_{1j} \cdots a_{1n} \\ a_{21}a_{22} \cdots a_{2j} \cdots a_{2n} \\ \vdots \\ a_{n1}a_{n2} \cdots a_{nj} \cdots a_{nn} \end{bmatrix}, \; X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}, \; Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}, \qquad \text{(A.6)}$$

simplified in matrix notation as:

$$(I - A)X = Y, \qquad \text{(A.7)}$$

and by rearrangement our question may then be answered by

$$X = (I - A)^{-1} Y, \text{ providing } |I - A| \neq 0 \qquad \text{(A.8)}$$

where $(I - A)^{-1}$ is known as the Leontief Inverse.

With $B = (I - A)^{-1}$, each b_{ij} represents not only the direct, but also the indirect (i.e. flow-on), requirements of industry i per unit of final demand for the output of industry j. The contribution made by an industry to an economy is thus not solely limited to the output it creates directly – an increase in final demand has repercussions throughout the entire economy, causing indirect increases in output beyond the initial change in final demand. In this way, the Leontief Inverse may be considered a powerful tool capable of capturing total effect (direct plus indirect) resulting from any exogenous final demand change.

A.5 Assumptions of Input-Output Modelling

The assumptions of input-output analysis are documented in detail elsewhere (see for example, Dorfman *et al.* (1958), Richardson (1972), O'Connor and Henry (1975), Leontief (1985) and Miller and Blair (1985)). In brief, the major assumptions may be summarised as:

- *Homogeneity assumption.* Each industry in an input-output matrix produces only one output. Implicit in this assumption is the notion that all businesses that constitute an industry use the same product mix in production of this one output.
- *Additivity assumption.* The total effect of carrying out several types of production is the sum of the separate effects. This implies the absence of any synergistic effects and external economies (diseconomies) of scale.
- *Linearity assumption.* The ratio of inputs to outputs decreases and increases in a linear manner. This also infers that there are no external economies (diseconomies) of scale.
- *Fixed coefficients of production assumption.* Inputs are required in fixed proportions to outputs in each industry. Inherently, this assumes that there are constant returns to scale in production, and that the elasticity of substitution between inputs is zero.
- *Temporal boundary assumption.* Input-output typically represents a snapshot of a financial year. All activity, direct or indirect, is assumed to be captured within the same year. In this way, activities planned for in advance must be internalised into the year of study i.e. assumed to have the same interdependencies as the study year.
- *Non-substitutability assumption.* This means that within a given technology there is one preferred set of input ratios that will continue to be preferred regardless of final demand quantities.

Appendix B

Global Biogeochemical Cycling Model

In this Appendix a system dynamics model of the global biogeochemical cycling processes is constructed – known as the Global Biogeochemical Cycling Model (GBCM). This model draws on the global elemental biogeochemical input-output flows estimated in Chapter 7. The focus of the GBCM is on the interactions and feedbacks between the biogeochemical cycles of carbon, hydrogen, phosphorus, sulphur and nitrogen. All results presented in this Appendix are preliminary and are meant only to illustrate the potential usefulness of the model. The GBCM is presented in Vensim® format in the Appendix B directory of the accompanying CD-ROM. The directory also contains the full program listing for the model – GBCM.txt.

B.1 Rationale for the Global Biogeochemical Cycling Model

The GBCM represents one of the first attempts globally to model the complex dynamic interrelationships and synergistic effects that exist between the biogeochemical cycles.[280] The coupling of the C, H, P, S and N cycles through ecological processes in the GBCM reveals the complex ecological cause-effect feedback chains that exist globally. These inextricably interconnected feedbacks form an organised whole, a complex system, the properties of which are more than the sum of its component parts. It is therefore argued that an integrated assessment of the biogeochemical cycles is thus required as: (1) many of the global environmental issues have common causes, and (2) these causes are intertwined with the biogeochemical cycles through complex feedback mechanisms. Furthermore, the GBCM permits the simulation of human perturbation of the environment – in particular, how the seemingly benign perturbation of one elemental cycle may result in considerable unforeseen impacts in other cycles or the overall biogeochemical system.[281]

There are several other salient features of the GBCM that distinguish it from its predecessors:

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[280] Other attempts include MacKenzie *et al.* (1993), den Elzen *et al.* (1995), Ayres (1996) and Smil (2002).

[281] Ayres (1996) questions the seemingly great faith that people have in the Earth's resilence to human perturbation. He argues that the fact that no catastrophe has yet eventuated is not evidence of inherent stability. He points to the well known tendency of complex non-linear systems to have multiple solutions or equilibria. A system may thus flip, as Thom's (1975) catastrophy theory suggests, from one equilibrium to another without warning.

- *Comprehensive recording of C, H, P, S and N flows.* The model's flows are based on Patterson's (2005) input-output model of ecological processes. This framework ensures materials balance of the C, H, P, S and N elements across each ecological process. This has been achieved by not only considering the major element flows associated with each biogeochemical process, but also sizeable flows of secondary reactants or by-products involving these elements. Other notable dynamic biogeochemical cycling models, such as those developed by Lerman *et al.* (1989), Mackenzie *et al.* (1993) and den Elzen *et al.* (1995) have largely ignored these supplementary flows.
- *What if implications.* A major benefit of the GBCM is that it may be used to investigate key controversies regarding the implications of human perturbation of the biogeochemical cycles. What are the possible implications on the biogeochemical cycles of, say, human induced disturbances such as land use intensification, or conversion of high quality land pasture surrounding cities into settlements, on global food production? What are the possible impacts on the H, N, P and S cycles of CO_2 fertilisation resulting from increased transport and manufacturing emissions?
- *Policy evaluation.* The GBCM model may also be utilised in the evaluation of environmental policies aimed at mitigating the impacts of human induced disturbance of the biogeochemical cycles, or alternatively, what tradeoffs exist between the various causes of biogeochemical disturbance.
- *Focus on geo-political governance.* The GBCM is probably the first attempt to model the complex interrelationships between the C, H, P, S and N cycles at a regional level. Other models have focused on microcosms, ecosystems or on global relationships and are therefore arguably divorced from the geo-political boundaries and human institutions often legislated with their guardianship.

The GBCM does not pretend to comprehensively evaluate all critical relationships within each cycle, or for that matter, between the C, H, P, S and N biogeochemical cycles. The complex dynamic nature of the GBCM is rather a consequence of the coupling of the elemental cycles – cycles which in their own right are typified by dynamic complex non-linear behaviour. This differs from the efforts of other researchers (see, for example, Bolin *et al.* (1979), Bowen (1979), Schlesinger (1991), Butcher *et al.* (1992), Charlson *et al.* (1992), Holman (1992), Jaffe (1992), Jahnke (1992), Gleick (1993), Wollast *et al.* (1993), Mackenzie and Mackenzie (1995) and Smil (1997, 2000, 2002)) who have largely focused on detailed analysis of (1) ecological processes, (2) more advanced models for individual cycles, and (3) static description of reservoirs and fluxes.

The GBCM adopts a systems approach as its guiding principle, the objective of which is not to study the elemental cycles in isolation, but instead to understand the complex feedback mechanisms and interrelationships that exist between the cycles. These feedbacks play a critical role in amplifying or dampening anthropogenic perturbations of ecological processes – the implications of which may be felt in several spheres, namely: the atmosphere, terrestrial biosphere, marine biosphere, hydrosphere and lithosphere. Such dynamics are captured in the GBCM using a quasi steady state box model consisting of a system of reservoirs (stocks) and processes (flows) connecting the reservoirs. The GBCM, like the ARDEEM, is modelled using the Vensim® DSS system dynamics software.

It is anticipated that the GBCM and a global equivalent of the ARDEEM model would in future revisions be coupled so that implications of both economic and environmental change may be traced in a totally integrated fashion. Before this interfacing can proceed, however, a number of modifications and improvements would need to be made to both models. Of particular concern, in the case of the GBCM, would be modification to include cross boundary spatial flows and the estimation of more localised effects. To some degree both of these modifications would require the development of dynamic spatial models – an area of research still very much in its infancy (see, for example, Costanza and Voinov (2004)).

B.2 Data Sources

The GCBM extends the ecological input-output table of Patterson (2002a, 2005) to investigate the longer term consequences, say, in the range of 50 to 100 years, of human perturbation of the C, H, P, S and N cycles. This extension requires the following additional datasets (1) the mass of key chemical species reservoirs (stocks), and (2) the transport (flow) rate of mass between reservoirs associated with each ecological process.

It should be noted that stock and flow estimates must be determined for the so-called pristine or pre-industrial state i.e. prior to, or at least excluding, anthropogenic perturbation (Mackenzie *et al.*, 1993; Ayres, 1996). This provides a baseline from which human induced impacts can be differentiated from naturally occurring consequences. Underpinning this requirement is the assumption that prior to human intervention the biogeochemical cycles were at, or near, steady state i.e. the reservoir (stock) masses were essentially constant or fluctuated within narrow bounds. This also means that the inflows and outflows of elemental mass of each stock must (on average) balance any chemical transformations from one species to another. Authors such as Ayres (1996) and Smil (2002) have however questioned this assumption – at least its long term validity. They argue that the biogeochemical cycles, over geological time scales, are seldom in balance as a consequence of changes resulting from tectonic, volcanic and climatic processes.[282] It is therefore theoretically inappropriate to compare current values of chemical species reservoirs with hypothetical steady state conditions.

B.2.1 Global Fluxes

This Section provides details on the model's global biogeochemical fluxes as obtained from Patterson's (2005) ecological input-output model.[283] Patterson (2002a, 2005) describes global biogeochemical cycling in annualised mass and energy terms using approximately 120 biogeochemical processes and 80 reservoirs, which are in turn, aggregated in the GBCM for ease of analytical use to 73 biogeochemical processes and 21 reservoirs.[284] Patterson's (2002a, 2005) fluxes of mass and energy were derived from a comprehensive literature review of previously undertaken studies, this included *inter alia* notable contributions made by Bolin *et al.* (1979), Bowen (1979), Schlesinger (1991), Butcher *et al.* (1992), Charlson *et al.* (1992), Holman (1992), Jaffe (1992), Jahnke (1992), Gleick (1993), Mackenzie *et al.* (1993), Wollast *et al.* (1993), den Elzen *et al.* (1995), Mackenzie and Mackenzie (1995), Ayres (1996) and Smil (1997, 2000, 2002). A recurrent theme stressed throughout this literature is that the estimation of biogeochemical fluxes is difficult, imprecise and often contentious – all results must therefore be treated cautiously.

The GBCM fluxes are depicted in Tables B.1 and B.2. Each biogeochemical process is described using a stiochiometrically balanced chemical equation – ensuring (elemental) mass balance. The chemical composition of the reactant side of each biogeochemical process is described in Table B.1. Biogeochemical processes are denoted in the rows, while reactant input chemical species (i.e. outputs from reservoirs), described in terms of elemental mass, are recorded in the columns. Global oxidation of land humus, for example, is described chemically as:

$$C_{800}H_{1000}O_{600}N_{32}S_4P + 808O_2 \rightarrow$$

[282] Ayres (1996) suggests that the biogeochemical cycles may be characterised as 'dissipative structures' that are far from thermodynamic equilibrium – as per the work of Nicolis and Prigogine (1977). Moreover, the C, P, S and N cycles, while consisting of both geochemical (slow) and biological (fast) processes, are thermodynamically driven by oxidation-reduction processes that approach a stable (i.e. lowest energy) thermodynamic state.

[283] The fluxes are recorded in aggregative form in Patterson (2002a).

[284] It is important to note that each biogeochemical process may in fact summarise several sequential steps, or chain reactions, that occur during the transformation of one chemical species to another. Similarly, each reservoir is an aggregation of several chemical species. Ideally, the number of biogeochemical processes and reservoirs should be maximised to provide as much insight as possible – for reasons of analytical ease of use and reporting this is not however always possible.

$$800CO_2 + 500H_2O + 32NO_3^- + PO_4^{3-} + 4SO_4^{2-}. \quad (B.1)$$

Thus, from Table B.1 the C mass flux resulting from the oxidation of land humus is estimated to be 40.2 Pg per year – derived solely from land humus ($C_{800}H_{1000}O_{600}S_4P$). The mass of the remaining elements that comprise land humus may be determined stiochiometrically. By contrast, Table B.2 describes the chemical composition of the product side of each biogeochemical cycling process. Once again, the biogeochemical processes are recorded in the rows and the product output chemical species (i.e. inputs to reservoirs) in the columns.

Table B.1 Biosphere Inputs Into Processes

	Cycle	Biogeochemical Process	Chemical Equation	Marker Element Mass Pg
1	C	oxidation of land humus	$C_{800}H_{1000}O_{600}N_{32}S_4P + 808O_2 \rightarrow 800CO_2 + 500H_2O + 32NO_3 + PO_4^{3-} + 4SO_4^{2-}$	40 1885
2	C	volcanic action	$C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2 + 34O_2 \rightarrow 100CO_2 + 700H_2O + 32PO_4^{3-} + 20SO_2 + N_2$	0.0082
3	C	land plant respiration	$C_{750}H_{1500}O_{750}N_{15}S_4P + 782.5O_2 \rightarrow 750CO_2 + 750H_2O + 15\ NO_3^- + 4\ SO_4^{2-} + PO_4^{3-}$	90 0033
4	C	tropospheric oxidation of CO	$2CO + O_2 \rightarrow 2CO_2$	1.4820
5	C	release of CO_2	$HCO_3^{2-} + H^+ \rightarrow CO_2 + H_2O$	64 9949
6	C	absorption of CO_2	$CO_2 + H_2O \rightarrow HCO_3^- + H^+$	70.7082
7	C	gross land production	$750CO_2 + 750H_2O + 15NO_3^- + 4SO_4^{2-} + PO_4^{3-} \rightarrow C_{750}H_{1500}O_{750}N_{15}S_4P + 782.5O_2$	142 5052
8	C	production of CO	$C_{100}H_{250}O_{140}N_{16}SP + 70\ 5O_2 + H^+ \rightarrow 100CO + 125H_2O + 16NO_3 + SO_4 + HPO_4$	0 1100
9	C	oxidation of CH_4	$CH_4 + 1.5O_2 \rightarrow CO + 2H_2O$	1 5460
10	C	sorption of CO	$800CO + 500H_2O + 32NO_3 + 4SO_4 + PO_4 \rightarrow C_{800}H_{1000}O_{500}N_{32}S_4P + 408O_2$	0 1900
11	C	production of CH_4	$C_{250}H_{500}O_{100}N_{50}P_3S + 125H_2O \rightarrow 150CH_4 + 100CO_2 + 50NH_3 + 3PO_4 + SO_4 + 4\ 5O_2$	0.5612
12	C	land humus formation (p)	$2C_{750}H_{1500}O_{750}N_{15}PS_4 + 353O_2 + 18NO_3 \rightarrow 1\ 5C_{800}H_{1000}O_{600}S_4P + 300CO_2 + 750H_2O + 0\ 5PO_4 + 2\ SO_4$	45 0966
13	C	land consumption	$C_{750}H_{1500}O_{750}N_{15}S_4P + 135NO_3 + 8PO_4 \rightarrow 3C_{250}H_{500}O_{100}N_{50}P_3S + SO_4 + 441\ 5O_2$	0 9611
14	C	gross marine production	$100\ HCO_3^- + 4NO_3^- + HPO_4^{3-} + SO_4^{2-} + 25H_2O \rightarrow C_{100}H_{150}O_{80}N_4SP + 132\ 5O_2 + H^+$	40.7666
15	C	marine plant respiration	$C_{100}H_{150}O_{80}N_4SP + 132\ 5O_2 + H^+ \rightarrow 100HCO_3^- + 4NO_3^- + HPO_4^{3-} + SO_4^{2-} + 25H_2O$	11 9990
16	C	production of $CaCO_3$	$C_{100}H_{150}O_{80}N_4SP + 157\ 5O_2 + 100Ca^{2+} + H^+ \rightarrow 100CaCO_3 + 4NO_3^- + HPO_4^{3-} + SO_4^{2-} + 75H_2O$	1 0999
17	C	marine humus formation (p)	$C_{100}H_{150}O_{80}N_4SP + 9O_2 \rightarrow C_{100}H_{120}O_{80}N_3PS + 15H_2O + NO_3$	23 5986
18	C	marine consumption	$C_{100}H_{150}O_{80}N_4SP + 50H_2O + 12NO_3 \rightarrow C_{100}H_{250}O_{140}N_{16}SP + 13O_2$	0 3800
19	C	land humus formation (c&d)	$4C_{250}H_{500}O_{100}N_{50}P_3S + 824O_2 \rightarrow C_{800}H_{1000}O_{800}N_{32}S_4P + 200CO_2 + 168NO_3 + 500H_2O + 11PO_4$	0 4000
20	C	marine humus formation (c&d)	$C_{100}H_{250}O_{140}N_{16}SP + 22O_2 \rightarrow C_{100}H_{120}O_{80}N_3PS + 13NO_3 + 65H_2O$	0 2700
21	C	coal formation	$C_{800}H_{1000}O_{600}N_{32}S_4P + 2SO_4^{2-} \rightarrow 6C_{130}H_{110}O_{10}N_2S + 20CO + 170H_2O + 10N_2 + 177O_2 + PO_4$	0 0075
22	C	transfer of land humus	$C_{800}H_{1000}O_{500}N_{32}S_4P + 7HPO_4 + 4SO_4 + 20O_2 \rightarrow 8C_{100}H_{120}O_{80}N_3PS + 8NO_3 + 20H_2O + 7H^+$	0.4000
23	C	oxidation of marine humus	$C_{100}H_{120}O_{80}N_3PS + 104H_2O + 60O_2 \rightarrow 100HCO_3^- + 108H_2 + HPO_4^{3-} + H_2S + 3NH_3$	20 9983
24	C	kerogen formation	$7C_{100}H_{120}O_{50}N_3PS + 280H_2O + 21SO_4^{2-} + 413O_2 \rightarrow C_{700}H_{1400}O_{1750}S_{28}P_7N_{14} + 3\ 5N_2$	0 5000
25	C	formation of limestone	$CaCO_3 \rightarrow CaCO_3$	0 3500
26	C	weathering of limestone	$CaCO_3 + H^+ \rightarrow HCO_3 + Ca^{2+}$	0 3500
27	C	igneous rock formation	$C_{700}H_{1400}O_{1750}S_{28}P_7N_{14} + 183O_2 + 25HPO_4^{3-} \rightarrow C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2 + 8SO_2 + 6N_2 + 600CO_2 + 25H^+$	0 0006
28	N	reduction of N_2O	$2N_2O \rightarrow 2N_2 + O_2$	0.0300
29	N	oxidation of N_2	$2N_2 + O_2 \rightarrow 2N_2O$	0 0150
30	N	marine dentrification	$2NO_3 + 12H^+ \rightarrow N_2 + 6H_2O$	0 0270
31	N	NOx formation by lightning	$2N_2 + 3O_2 \rightarrow 2NO + 2NO_2$	0.0100
32	N	biological fixation by phytoplankton	$400CO_2 + 300H_2O + 4SO_4 + 4HPO_4 + N_2O + 7N_2 \rightarrow 4C_{100}H_{150}O_{80}N_4SP + 406\ 5O_2 + 4H^+$	0.0400
33	N	release of N2 & N2O	$4C_{100}H_{150}O_{80}N_4SP + 4H^+ + 406\ 5O_2 \rightarrow 400CO_2 + 300H_2O + 4SO_4 + 4HPO_4 + N_2O + 7N_2$	0 0400
34	N	microbial production of N2 & N2O	$C_{800}H_{1000}O_{600}N_{32}S_4P + 635\ 5O_2 \rightarrow 800CO_2 + 248H_2O + 13N_2 + 3N_2O + PO_4^{3-} + 4SO_4 + 504H^+$	0 2425
35	N	uptake of N2 & N2O	$800CO_2 + 248H_2O + 3N_2O + 13N_2 + PO_4^{3-} + 4SO_4 + 504H^+ \rightarrow C_{800}H_{1000}O_{800}N_{32}S_4P + 635\ 5O_2$	0 1847
36	N	photochemical oxidation of N_2O	$N_2O + O_2 \rightarrow NO + NO_2$	0 0050
37	N	wet deposition of NOx	$NO_{1\ 5} + 0\ 75O_2 \rightarrow NO_3^-$	0 0150
38	N	acid rain	$NO_{15} + 0\ 75O_2 \rightarrow NO_3$	0.0130
39	N	microbial production of NH_3	$C_{800}H_{1000}O_{600}N_{32}S_4P + 364H_2O \rightarrow 480CO_2 + 320CH_4 + 32NH_3 + 172H_2 + 4H_2S + PO_4$	0.0840
40	N	uptake of NH_3 by soil	$480CO_2 + 320CH_4 + 32NH_3 + 172H_2 + 4H_2S + PO_4 \rightarrow C_{800}H_{1000}O_{600}N_{32}S_4P + 364H_2O$	0.0540
41	N	uptake of NH_3 by ocean	NH_3 (gas) $\rightarrow NH_3$ (dissolved)	0.1396
42	N	N runoff	NO_3^- (soil) $\rightarrow NO_3^-$ (ocean)	0 0320
43	N	sedimentary N rock formation	$NO_3^- + 4H^+ \rightarrow NH_4^+ + 1\ 5O_2$	0.0150
44	N	weathering of sedimentary N rock	$NH_4^+ + 1.5O_2 \rightarrow NO_3 + 4H^+$	0.0050
45	S	release of H_2S	$C_{100}H_{150}O_{80}N_4SP + 28H_2O \rightarrow 48CH_4 + 52CO_2 + H_2S + 4NH_3 + PO_4^{3-}$	0 0550
46	S	ocean spray of SO_4	$SO_4^{2-} \rightarrow SO_2 + O_2$	0.0440
47	S	uptake of SO_2 by ocean	$SO_2 + O_2 \rightarrow SO_4^{2}$	0.0960
48	S	uptake of SO_2 by soil	$SO_2 + O_2 \rightarrow SO_4^{2-}$	0 1160
49	S	ocean spray to land	$SO_4^{2-} \rightarrow SO_4^{2-}$	0.0040
50	S	S runoff	$SO_4^{2-} \rightarrow SO_4^{2-}$	0 1329
51	S	S sedimentation	$SO_4^{2-} \rightarrow SO_4^{2}$	0 0550
52	S	sedimentary S rock formation	$SO_4 \rightarrow S^{2-} + 2O_2$	0 0550
53	S	uplift & weathering of sedimentary S rock	$S^{2-} + 2O_2 \rightarrow SO_4^{2-}$	0 0470
54	S	H_2S dissolution	$H_2S + 4H_2O \rightarrow SO_4^{2-} + 2H^+ + 4H_2$	0 4606
55	P	weathering of sedimentary P rock	$Ca_5(PO_4)_3(OH)$ (sediment) $\rightarrow 5Ca^{2+} + 3PO_4^{3-} + OH$	0.0214
56	P	soil to ocean P sediments	$5Ca^{2+} + 3PO_4^{3-} + OH^- \rightarrow Ca_5(PO_4)_3(OH)$	0 0187
57	P	P runoff	$PO_4^{3-} + H^+ \rightarrow HPO_4^{2}$	0.0180
58	P	evaporation of soluble P	$3HPO_4^{2-} + 5Ca^{2+} + 3OH^- \rightarrow Ca_5(PO_4)_3(OH) + 2H_2O + H^+$	0 0003
59	P	deposition of soluble P	$Ca_5(PO_4)_3(OH) + 2H_2O + H^+ \rightarrow 3HPO_4^{2-} + 5Ca^{2+} + 3OH^-$	0 0005
60	P	deposition of insoluble P	$Ca_5(PO_4)_3(OH)$ (atmosphere) $\rightarrow Ca_5(PO_4)_3(OH)$ (sediments)	0 0008
61	P	P particulate flux	$C_{100}H_{150}O_{80}N_4SP + 108O_2 + 3H^+ \rightarrow 100CO_2 + 76H_2O + 4NO_3 + SO_4^{2-} + HPO_4^{2}$	0.0420
62	P	formation of atmospheric P dust particles	$5Ca + OH + 3PO_4 \rightarrow Ca_5(PO_4)_3OH$	0 0031
63	P	dissolution of atmospheric P dust particles	$Ca_5(PO_4)_3OH \rightarrow 5Ca + OH + 3PO_4$	0.0021
64	P	P sedimentation	$6\ HPO_4^{2-} + 10Ca^{2+} + 8OH^- \rightarrow 2Ca_5(PO_4)_3(OH) + 6H_2O$	0.0019
65	P	sedimentary P rock formation	$Ca_5(PO_4)_3(OH)$ (marine sediments) $\rightarrow Ca_5(PO_4)_3(OH)$ (uplifted sediments)	0.0214
66	H	transpiration	H_2O (liquid) $\rightarrow H_2O$ (gas)	3,000.0587
67	H	evaporation from ocean	H_2O (liquid) $\rightarrow H_2O$ (gas)	43,000.8411
68	H	precipitation to ocean	H_2O (gas) $\rightarrow H_2O$ (liquid)	39,000.7629
69	H	precipitation to land	H_2O (gas) $\rightarrow H_2O$ (liquid)	11,004 6122
70	H	evaporation from land	H_2O (liquid) $\rightarrow H_2O$ (gas)	4,000.0782
71	H	uptake of H_2O	H_2O (liquid) $\rightarrow H_2O$ (liquid)	3,0000587
72	H	photooxidation of H_2	$H_2 + 0\ 5O_2 \rightarrow H_2O$	3.9864
73	H	river discharge	H_2O (liquid) $\rightarrow H_2O$ (liquid)	3,955.4374

Table B.1 Biosphere Inputs Into Processes (Continued)

	Cycle	Biogeochemical Process	1st Reactant: Chemical Species	1st Reactant: Origin Reservoir	1st Reactant: Mass (Pg)	2nd Reactant: Chemical Species	2nd Reactant: Origin Reservoir	2nd Reactant: Mass (Pg)
1	C	oxidation of land humus	$C_{800}H_{1000}O_{800}N_{32}S_4P$	Land humus	87 1010	$808O_2$	O_2	108 1509
2	C	volcanic action	$C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2$	Igneous rock	0 1384	$34O_2$	O_2	0.0074
3	C	land plant respiration	$C_{750}H_{1500}O_{750}N_{15}S_4P$	Land plants	228 7064	$782.5O_2$	O_2	250.2007
4	C	tropospheric oxidation of CO	2CO	Atmosphere NEC	3 4563	O_2	O_2	1 9743
5	C	*release of CO_2*	*HCO_3^{2}*	*Ocean NEC*	*3302133*	*H^+*	*Ocean NEC*	5 4550
6	C	absorption of CO_2	CO_2	Atmosphere CO_2	259 1065	H_2O	Ocean H_2O	106.0682
7	C	gross land production	$750CO_2$	Atmosphere CO_2	522 2028	$750H_2O$	Fresh water H_2O	213 7697
8	C	production of CO	$C_{100}H_{250}O_{140}N_{16}SP$	Marine cons /decomps	0 3645	$70\ 5O_2$	O_2	0 2066
9	C	oxidation of CH_4	CH_4	Atmosphere CH_4	2 0650	$1\ 5O_2$	O_2	6 1787
10	C	sorption of CO	800CO	Atmosphere NEC	0.4431	$500H_2O$	Fresh water H_2O	0 1781
11	C	production of CH_4	$C_{250}H_{500}O_{100}N_{50}P_3S$	Land cons /decomps	1 1087	$125H_2O$	Fresh water H_2O	0 4209
12	C	land humus formation (p)	$2C_{750}H_{1500}O_{750}N_{15}PS_4$	Land plants	114 5946	$353O_2$	O_2	282771
13	C	land consumption	$C_{750}H_{1500}O_{750}N_{15}S_4P$	Land plants	2 4424	$135NO_3$	Soil	0 8933
14	C	gross marine production	$100HCO_3$	Ocean NEC	207 1190	$4NO_3$	Ocean NEC	8.4194
15	C	*marine plant respiration*	$C_{100}H_{150}O_{80}N_4SP$	*Marine plants*	27 4876	$132\ 5O_2$	O_2	423613
16	C	production of $CaCO_3$	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	2 5197	$157\ 5O_2$	O_2	4 6157
17	C	marine humus formation (p)	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	54 0601	$9O_2$	O_2	5 6590
18	C	marine consumption	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	0 8704	$50H_2O$	Ocean H_2O	0 2850
19	C	land humus formation (c&d)	$4C_{250}H_{500}O_{100}N_{50}P_3S$	Land cons /decomps	0 7902	$824O_2$	O_2	0 8781
20	C	marine humus formation (c&d)	$C_{100}H_{250}O_{140}N_{16}SP$	Marine cons /decomps	0 8947	$22O_2$	O_2	0 1583
21	C	coal formation	$C_{800}H_{1000}O_{800}N_{32}S_4P$	Land humus	0 0163	$2SO_4^{2}$	Soil	0 0001
22	C	transfer of land humus	$C_{800}H_{1000}O_{800}N_{32}S_4P$	Land humus	0 8669	$7HPO_4$	Ocean NEC	0 0280
23	C	oxidation of marine humus	$C_{100}H_{120}O_{80}N_3PS$	Marine humus	47 3297	$104H_2O$	Ocean H_2O	32 7592
24	C	kerogen formation	$7C_{100}H_{120}O_{80}N_3PS$	Marine humus	1 1269	$280H_2O$	Ocean H_2O	0 3000
25	C	formation of limestone	$CaCO_3$	Ocean NEC	2 9166			
26	C	weathering of limestone	$CaCO^{3}$	Sedimentary rock	2 9166	H^+	Soil	0 0294
27	C	igneous rock formation	[illegible]	Fossil fuels	0 0028	$183O_2$	O_2	0 0004
28	N	reduction of N_2O	$2N_2O$	Atmosphere N_2O	0 0471			
29	N	oxidation of N_2	$2N_2$	Atmosphere N_2	0 0150	O_2	O_2	0 0086
30	N	marine dentrification	$2NO_3$	Ocean NEC	0 1195	$12H^+$	Ocean NEC	0 0117
31	N	NOx formation by lightning	$2N_2$	Atmosphere N_2	0 0100	$3O_2$	O_2	0 0171
32	N	biological fixation by phytoplankton	$400CO_2$	Atmosphere CO_2	3 1420	$300H_2O$	Ocean H_2O	0 9647
33	N	release of N_2 & N_2O	$4C_{100}H_{150}O_{80}N_4SP$	Marine plants	1 9642	$4H^+$	Ocean NEC	0 0007
34	N	microbial production of N_2 & N_2O	$C_{800}H_{1000}O_{800}N_{32}S_4P$	Land humus	11 2643	$635\ 5O_2$	O_2	11 0005
35	N	uptake of N_2 & N_2O	$800CO_2$	Atmosphere CO_2	14 5016	$248H_2O$	Fresh water H_2O	1 8403
36	N	photochemical oxidation of N_2O	N_2O	Atmosphere N_2O	0 0079	O_2	O_2	0.0057
37	N	wet deposition of NOx	$NO_{1\ 5}$	Atmosphere NEC	0 0407	$0\ 75O_2$	O_2	0.0257
38	N	acid rain	$NO_{1\ 5}$	Atmosphere NEC	0 0353	$0\ 75O_2$	O_2	0.0223
39	N	microbial production of NH_3	$C_{800}H_{1000}O_{800}N_{32}S_4P$	Land humus	3 9025	$364H_2O$	Fresh water H_2O	1 2290
40	N	uptake of NH_3 by soil	$480CO_2$	Atmosphere CO_2	2 5450	$320CH_4$	Atmosphere CH_4	0 6185
41	N	uptake of NH_3 by ocean	NH_3 (gas)	Atmosphere NEC	0 1698			
42	N	*N runoff*	*NO_3 (soil)*	*Soil*	0 1417			
43	N	sedimentary N rock formation	NO_3	Ocean NEC	0 0664	$4H^+$	Ocean NEC	0 0043
44	N	weathering of sedimentary N rock	NH_4^+	Sedimentary rock	0 0064	$1\ 5O_2$	O_2	0.0171
45	S	release of H_2S	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	4 7205	$28H_2O$	Ocean H_2O	0 8655
46	S	ocean spray of SO_4	SO_4^{2-}	Ocean NEC	0.1318			
47	S	uptake of SO_2 by ocean	SO_2	Atmosphere NEC	0.1918	O_2	O_2	0 0958
48	S	uptake of SO_2 by soil	SO_2	Atmosphere NEC	0 2317	O_2	O_2	0 1158
49	S	ocean spray to land	SO_4^{2-}	Ocean NEC	0 0120			
50	S	S runoff	SO_4^{2}	Soil	0 3982			
51	S	S sedimentation	SO_4^{2-}	Ocean NEC	0 1648			
52	S	*sedimentary S rock formation*	SO_4	*Marine sediments*	*0 1648*			
53	S	uplift & weathering of sedimentary S rock	S^{2-}	Sedimentary rock	0 0470	$2O_2$	O_2	0 0938
54	S	H_2S dissolution	H_2S	Atmosphere NEC	0 4896	$4H_2O$	Atmosphere H_2O	1 0353
55	P	weathering of sedimentary P rock	$Ca_5(PO_4)_3(OH)$	Sedimentary Rock	0 1157			
56	P	soil to ocean P sediments	$5Ca^{2+}$	Soil	0.0403	$3PO_4^{3-}$	Soil	0 0573
57	P	P runoff	PO_4^{3-}	Soil	0 0552	H^+	Soil	0 0006
58	P	evaporation of soluble P	$3HPO_4^{2}$	Ocean NEC	0 0009	$5Ca^{2+}$	Ocean NEC	0 0006
59	P	deposition of soluble P	$Ca_5(PO_4)_3(OH)$	Atmosphere NEC	0 0027	$2H_2O$	Atmosphere H_2O	0 0002
60	P	deposition of insoluble P	$Ca_5(PO_4)_3(OH)$	Atmosphere NEC	0 0043			
61	P	P particulate flux	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	3 7306	$108O_2$	O_2	4 6862
62	P	*formation of atmospheric P dust particles*	*5Ca*	*Soil*	*0.0067*	*OH*	*Soil*	*0 0006*
63	P	dissolution of atmospheric P dust particles	$Ca_5(PO_4)_3OH$	Atmosphere NEC	0 0114			
64	P	P sedimentation	$6HPO_4^{2}$	Ocean NEC	0 0059	$10Ca^{2+}$	Ocean NEC	0 0041
65	P	sedimentary P rock formation	$Ca_5(PO_4)_3(OH)$	Marine sediments	0.1157			
66	H	transpiration	H_2O	Land plants	26,810.0482			
67	H	evaporation from ocean	H_2O	Ocean H_2O	384,277 3578			
68	H	precipitation to ocean	H_2O	Atmosphere H_2O	348,530 6268			
69	H	precipitation to land	H_2O	Atmosphere H_2O	98,342.8045			
70	H	evaporation from land	H_2O	Fresh water H_2O	35,746 7310			
71	H	uptake of H_2O	H_2O	Fresh water H_2O	26,810 0482			
72	H	*photooxidation of H_2*	*H_2*	*Atmosphere NEC*	3.9864	*$0.5O_2$*	*O_2*	31 6378
73	H	river discharge	H_2O	Fresh water H_2O	35,347 7974			

Table B.1 Biosphere Inputs Into Processes (Continued)

	Cycle	Biogeochemical Process	3rd Reactant			4th Reactant			5th Reactant		
			Chemical Species	Origin Reservoir	Mass (Pg)	Chemical Species	Origin Reservoir	Mass (Pg)	Chemical Species	Origin Reservoir	Mass (Pg)
1	C	oxidation of land humus									
2	C	volcanic action									
3	C	land plant respiration									
4	C	tropospheric oxidation of CO									
5	C	release of CO_2									
6	C	absorption of CO_2									
7	C	gross land production	$15NO_3$	Soil	14 7157	$4SO_4^{2-}$	Soil	6 0790	PO_4^{3-}	Soil	1 5025
8	C	production of CO	H^+	Ocean NEC	0 0001						
9	C	oxidation of CH_4									
10	C	sorption of CO	$32NO_3$	Soil	0 0392	$4SO_4$	Soil	0 0076	PO_4	Soil	0 0019
11	C	production of CH_4									
12	C	land humus formation (p)	$18NO^3$	Soil	2 7941						
13	C	land consumption	$8PO_4$	Soil	0 0811						
14	C	gross marine production	HPO_4^3	Ocean NEC	3 2579	SO_4^{2-}	Ocean NEC	3 2607	$25H_2O$	Ocean H_2O	15 2883
15	C	marine plant respiration	H^+	Ocean NEC	0 0101						
16	C	production of $CaCO_3$	$100Ca^{2+}$	Ocean NEC	3 6706	H^+	Ocean NEC	0 0009			
17	C	marine humus formation (p)									
18	C	marine consumption	$12NO_3^-$	Ocean NEC	0 2354						
19	C	land humus formation (c&d)									
20	C	marine humus formation (c&d)									
21	C	coal formation									
22	C	transfer of land humus	$4SO_4$	Ocean NEC	0 0160	$20O_2$	O_2	0 0266			
23	C	oxidation of marine humus	$60O_2$	O_2	33 5694						
24	C	kerogen formation	$21SO_4^{2-}$	Ocean NEC	0 1200	$413O_2$	O_2	0.7860			
25	C	formation of limestone									
26	C	weathering of limestone									
27	C	igneous rock formation	$25HPO_4^{3-}$	Ocean NEC	0.0002						
28	N	reduction of N_2O									
29	N	oxidation of N_2									
30	N	marine dentrification									
31	N	NOx formation by lightning									
32	N	biological fixation by phytoplankton	$4SO_4$	Ocean NEC	0 0686	$4HPO_4$	Ocean NEC	0 0585	N_2O	Atmosphere N_2O	0 0079
33	N	release of N_2 & N_2O	$406\ SO_2$	O_2	2 3217						
34	N	microbial production of N_2 & N_2O									
35	N	uptake of N_2 & N_2O	$3N_2O$	Atmosphere N_2O	0.0544	$13N_2$	Atmosphere N2	0 1500	PO_4^{3-}	Soil	0 0391
36	N	photochemical oxidation of N_2O									
37	N	wet deposition of NOx									
38	N	acid rain									
39	N	microbial production of NH_3									
40	N	uptake of NH_3 by soil	$32NH_3$	Atmosphere NEC	0 0657	$172H_2$	Atmosphere NEC	0 0418	$4H_2S$	Atmosphere NEC	0 0164
41	N	uptake of NH_3 by ocean									
42	N	N runoff									
43	N	sedimentary N rock formation									
44	N	weathering of sedimentary N rock									
45	S	release of H_2S									
46	S	ocean spray of SO_4									
47	S	uptake of SO_2 by ocean									
48	S	uptake of SO_2 by soil									
49	S	ocean spray to land									
50	S	S runoff									
51	S	S sedimentation									
52	S	sedimentary S rock formation									
53	S	uplift & weathering of sedimentary S rock									
54	S	H_2S dissolution									
55	P	weathering of sedimentary P rock									
56	P	soil to ocean P sediments	OH^-	Soil	0.0034						
57	P	P runoff									
58	P	evaporation of soluble P	3OH	Ocean NEC	0.0002						
59	P	deposition of soluble P	H+	Atmosphere NEC	0 0000						
60	P	deposition of insoluble P									
61	P	P particulate flux	$3H^+$	Ocean NEC	0 0041						
62	P	formation of atmospheric P dust particles	$3PO_4$	Soil	0.0095						
63	P	dissolution of atmospheric P dust particles									
64	P	P sedimentation	$8OH^-$	Ocean NEC	0 0014						
65	P	sedimentary P rock formation									
66	H	transpiration									
67	H	evaporation from ocean									
68	H	precipitation to ocean									
69	H	precipitation to land									
70	H	evaporation from land									
71	H	uptake of H_2O									
72	H	photooxidation of H_2									
73	H	river discharge									

Table B.1 Biosphere Inputs Into Processes (Continued)

	Cycle	Biogeochemical Process	6th Reactant Chemical Species	6th Reactant Origin Reservoir	6th Reactant Mass	7th Reactant Chemical Species	7th Reactant Origin Reservoir	7th Reactant Mass	Total Reactant Flux Mass
					Pg			Pg	Pg
1	C	oxidation of land humus							195 2518
2	C	volcanic action							0 1458
3	C	land plant respiration							478 9071
4	C	tropospheric oxidation of CO							5 4306
5	C	release of CO_2							335.6683
6	C	absorption of CO_2							365 1747
7	C	gross land production							758 2696
8	C	production of CO							0.5712
9	C	oxidation of CH_4							8.2437
10	C	sorption of CO							0 6699
11	C	production of CH_4							1 5296
12	C	land humus formation (p)							145 6658
13	C	land consumption							3 4167
14	C	gross marine production							237 3453
15	C	marine plant respiration							69 8590
16	C	production of $CaCO_3$							10 8069
17	C	marine humus formation (p)							59 7190
18	C	marine consumption							1 3909
19	C	land humus formation (c&d)							1.6683
20	C	marine humus formation (c&d)							1 0530
21	C	coal formation							0 0164
22	C	transfer of land humus							0 9375
23	C	oxidation of marine humus							113 6583
24	C	kerogen formation							2 3328
25	C	formation of limestone							2 9166
26	C	weathering of limestone							2 9460
27	C	igneous rock formation							0 0034
28	N	reduction of N_2O							0 0471
29	N	oxidation of N_2							0 0236
30	N	marine denitrification							0 1312
31	N	NOx formation by lightning							0 0271
32	N	biological fixation by phytoplankton	$7N_2$	Atmosphere N_2	0 0350				4 2866
33	N	release of N_2 & N_2O							4 2866
34	N	microbial production of N_2 & N_2O							22 2648
35	N	uptake of N_2 & N_2O	$4SO_4$	Soil	0 1583	$504H^+$	Soil	0 2092	16 9529
36	N	photochemical oxidation of N_2O							0 0136
37	N	wet deposition of NOx							0 0664
38	N	acid rain							0.0575
39	N	microbial production of NH_3							5 1315
40	N	uptake of NH_3 by soil	PO_4	Soil	0 0114				3 2988
41	N	uptake of NH_3 by ocean							0 1698
42	N	N runoff							0 1417
43	N	sedimentary N rock formation							0.0707
44	N	weathering of sedimentary N rock							0 0236
45	S	release of H_2S							5 5860
46	S	ocean spray of SO_4							0 1318
47	S	uptake of SO_2 by ocean							0 2876
48	S	uptake of SO_2 by soil							0 3475
49	S	ocean spray to land							0 0120
50	S	S runoff							0 3982
51	S	S sedimentation							0.1648
52	S	sedimentary S rock formation							0 1648
53	S	uplift & weathering of sedimentary S rock							0.1408
54	S	H_2S dissolution							1 5249
55	P	weathering of sedimentary P rock							0 1157
56	P	soil to ocean P sediments							0.1011
57	P	P runoff							0 0558
58	P	evaporation of soluble P							0 0017
59	P	deposition of soluble P							0 0029
60	P	deposition of insoluble P							0 0043
61	P	P particulate flux							8.4209
62	P	formation of atmospheric P dust particles							0 0168
63	P	dissolution of atmospheric P dust particles							0.0114
64	P	P sedimentation							0 0114
65	P	sedimentary P rock formation							0 1157
66	H	transpiration							26,810 0482
67	H	evaporation from ocean							384,277 3578
68	H	precipitation to ocean							348,530 6268
69	H	precipitation to land							98,342 8045
70	H	evaporation from land							35,746 7310
71	H	uptake of H_2O							26,810 0482
72	H	photooxidation of H_2							35 6241
73	H	river discharge							35,347.7974

Table B.2 Biosphere Outputs From Processes

Cycle		Vensim Processes	Chemical Equation	Marker Element Mass Pg
1	C	oxidation of land humus	$C_{800}H_{1000}O_{600}N_{32}S_4P + 808O_2 \rightarrow 800CO_2 + 500H_2O + 32NO_3 + PO_4^{3-} + 4SO_4^{2-}$	40.1885
2	C	volcanic action	$C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2 + 34O_2 \rightarrow 100CO_2 + 700H_2O + 32PO_4^{3-} + 20SO_2 + N_2$	0.0082
3	C	land plant respiration	$C_{750}H_{1500}O_{750}N_{15}S_4P + 782.5O_2 \rightarrow 750CO_2 + 750H_2O + 15NO_3^- + 4SO_4^{2-} + PO_4^{3-}$	90.0033
4	C	tropospheric oxidation of CO	$2CO + O_2 \rightarrow 2CO_2$	1.4820
5	C	release of CO_2	$HCO_3^{2-} + H^+ \rightarrow CO_2 + H_2O$	64.9949
6	C	absorption of CO_2	$CO_2 + H_2O \rightarrow HCO_3^- + H^+$	70.7082
7	C	gross land production	$750CO_2 + 750H_2O + 15NO_3^- + 4SO_4^{2-} + PO_4^{3-} \rightarrow C_{750}H_{1500}O_{750}N_{15}S_4P + 782.5O_2$	142.5052
6	C	production of CO	$C_{100}H_{250}O_{140}N_{16}SP + 70.5O_2 + H^+ \rightarrow 100CO + 125H_2O + 16NO_3 + SO_4 + HPO_4$	0.1100
9	C	oxidation of CH_4	$CH_4 + 1.5O_2 \rightarrow CO + 2H_2O$	1.5460
10	C	sorption of CO	$800CO + 500H_2O + 32NO_3 + 4SO_4 + PO_4 \rightarrow C_{800}H_{1000}O_{600}N_{32}S_4P + 408O_2$	0.1900
11	C	production of CH_4	$C_{250}H_{500}O_{100}N_{50}P_3S + 125H_2O \rightarrow 150CH_4 + 100CO_2 + 50NH_3 + 3PO_4 + SO_4 + 4.5O_2$	0.5612
12	C	land humus formation (p)	$2C_{750}H_{1500}O_{750}N_{15}PS_4 + 353O_2 + 18NO_3 \rightarrow 1.5C_{800}H_{1000}O_{600}S_4P + 300CO_2 + 750H_2O + 0.5PO_4 + 2SO_4$	45.0966
13	C	land consumption	$C_{750}H_{1500}O_{750}N_{15}S_4P + 135NO_3 + 8PO_4 \rightarrow 3C_{250}H_{500}O_{100}N_{50}P_3S + SO_4 + 441.5O_2$	0.9611
14	C	gross marine production	$100HCO_3 + 4NO_3 + HPO_4^{3-} + SO_4^{2-} + 25H_2O \rightarrow C_{100}H_{150}O_{80}N_4SP + 132.5O_2 + H^+$	40.7666
15	C	marine plant respiration	$C_{100}H_{150}O_{80}N_4SP + 132.5O_2 + H^+ \rightarrow 100HCO_3 + 4NO_3 + HPO_4^{3-} + SO_4^{2-} + 25H_2O$	11.9990
16	C	production of $CaCO_3$	$C_{100}H_{150}O_{80}N_4SP + 157.5O_2 + 100Ca^{2+} + H^+ \rightarrow 100CaCO_3 + 4NO_3^- + HPO_4^{3-} + SO_4^{2-} + 75H_2O$	1.0999
17	C	marine humus formation (p)	$C_{100}H_{150}O_{80}N_4SP + 9O_2 \rightarrow C_{100}H_{120}O_{80}N_3PS + 15H_2O + NO_3$	23.5986
18	C	marine consumption	$C_{100}H_{150}O_{80}N_4SP + 50H_2O + 12NO_3 \rightarrow C_{100}H_{250}O_{140}N_{16}SP + 13O_2$	0.3800
19	C	land humus formation (c&d)	$4C_{250}H_{500}O_{100}N_{50}P_3S + 824O_2 \rightarrow C_{800}H_{1000}O_{600}N_{32}S_4P + 200CO_2 + 168NO_3 + 500H_2O + 11PO_4$	0.4000
20	C	marine humus formation (c&d)	$C_{100}H_{250}O_{140}N_{16}SP + 22O_2 \rightarrow C_{100}H_{120}O_{80}N_3PS + 13NO_3 + 65H_2O$	0.2700
21	C	coal formation	$C_{800}H_{1000}O_{600}N_{32}S_4P + 2SO_4^{2-} \rightarrow 6C_{130}H_{110}O_{10}N_2S + 20CO + 170H_2O + 10N_2 + 177O_2 + PO_4$	0.0075
22	C	transfer of land humus	$C_{800}H_{1000}O_{600}N_{32}S_4P + 7HPO_4 + 4SO_4 + 20O_2 \rightarrow 8C_{100}H_{120}O_{80}N_3PS + 8NO_3 + 20H_2O + 7H^+$	0.4000
23	C	oxidation of marine humus	$C_{100}H_{120}O_{80}N_3PS + 104H_2O + 60O_2 \rightarrow 100HCO_3^- + 108H_2 + HPO_4^{3-} + H_2S + 3NH_3$	20.9983
24	C	kerogen formation	$7C_{100}H_{120}O_{80}N_3PS + 280H_2O + 21SO_4^{2-} + 413O_2 \rightarrow C_{700}H_{1400}O_{1750}S_{28}P_7N_{14} + 3.5N_2$	0.5000
25	C	formation of limestone	$CaCO_3 \rightarrow CaCO_3$	0.3500
26	C	weathering of limestone	$CaCO_3 + H^+ \rightarrow HCO_3^- + Ca^{2+}$	0.3500
27	C	igneous rock formation	$C_{700}H_{1400}O_{1750}S_{28}P_7N_{14} + 183O_2 + 25HPO_4^{3-} \rightarrow C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2 + 8SO_2 + 6N_2 + 600CO_2 + 25H^+$	0.0006
28	N	reduction of N_2O	$2N_2O \rightarrow 2N_2 + O_2$	0.0300
29	N	oxidation of N_2	$2N_2 + O_2 \rightarrow 2N_2O$	0.0150
30	N	marine denitrification	$2NO_3 + 12H^+ \rightarrow N_2 + 6H_2O$	0.0270
31	N	NOx formation by lightning	$2N_2 + 3O_2 \rightarrow 2NO + 2NO_2$	0.0100
32	N	biological fixation by phytoplankton	$400CO_2 + 300H_2O + 4SO_4 + 4HPO_4 + N_2O + 7N_2 \rightarrow 4C_{100}H_{150}O_{80}N_4SP + 406.5O_2 + 4H^+$	0.0400
33	N	release of N_2 and N_2O	$4C_{100}H_{150}O_{80}N_4SP + 4H^+ + 406.5O_2 \rightarrow 400CO_2 + 300H_2O + 4SO_4 + 4HPO_4 + N_2O + 7N_2$	0.0400
34	N	microbial production of N_2 and N_2O	$C_{800}H_{1000}O_{800}N_{32}S_4P + 635.5O_2 \rightarrow 800CO_2 + 248H_2O + 13N_2 + 3N_2O + PO_4^{3-} + 4SO_4 + 504H^+$	0.2425
35	N	uptake of N_2 and N_2O	$800CO_2 + 248H_2O + 3N_2O + 13N_2 + PO_4^{3-} + 4SO_4 + 504H^+ \rightarrow C_{800}H_{1000}O_{800}N_{32}S_4P + 635.5O_2$	0.1847
36	N	photochemical oxidation of N_2O	$N_2O + O_2 \rightarrow NO + NO_2$	0.0050
37	N	wet deposition of NOx	$NO_{1.5} + 0.75O_2 \rightarrow NO_3^-$	0.0150
38	N	acid rain	$NO_{1.5} + 0.75O_2 \rightarrow NO_3$	0.0130
39	N	microbial production of NH_3	$C_{800}H_{1000}O_{600}N_{32}S_4P + 364H_2O \rightarrow 480CO_2 + 320CH_4 + 32NH_3 + 172H_2 + 4H_2S + PO_4$	0.0840
40	N	uptake of NH_3 by soil	$480CO_2 + 320CH_4 + 32NH_3 + 172H_2 + 4H_2S + PO_4 \rightarrow C_{800}H_{1000}O_{600}N_{32}S_4P + 364H_2O$	0.0540
41	N	uptake of NH_3 by ocean	NH_3 (gas) $\rightarrow$ NH_3 (dissolved)	0.1396
42	N	N runoff	NO_3^- (soil) $\rightarrow$ NO_3 (ocean)	0.0320
43	N	sedimentary N rock formation	$NO_3^- + 4H^+ \rightarrow NH_4^+ + 1.5O_2$	0.0150
44	N	weathering of sedimentary N rock	$NH_4^+ + 1.5O_2 \rightarrow NO_3 + 4H^+$	0.0050
45	S	release of H_2S	$C_{100}H_{150}O_{80}N_4SP + 28H_2O \rightarrow 48CH_4 + 52CO_2 + H_2S + 4NH_3 + PO_4^{3-}$	0.0550
46	S	ocean spray of SO_4	$SO_4^{2-} \rightarrow SO_2 + O_2$	0.0440
47	S	uptake of SO_2 by ocean	$SO_2 + O_2 \rightarrow SO_4^{2-}$	0.0960
48	S	uptake of SO_2 by soil	$SO_2 + O_2 \rightarrow SO_4^{2}$	0.1160
49	S	ocean spray to land	$SO_4^{2-} \rightarrow SO_4^{2-}$	0.0040
50	S	S runoff	$SO_4^{2-} \rightarrow SO_4^{2-}$	0.1329
51	S	S sedimentation	$SO_4^{2-} \rightarrow SO_4^{2-}$	0.0550
52	S	sedimentary S rock formation	$SO_4 \rightarrow S^{2-} + 2O_2$	0.0550
53	S	uplift and weathering of sedimentary S rock	$S^{2-} + 2O_2 \rightarrow SO_4^{2}$	0.0470
54	S	H_2S dissolution	$H_2S + 4H_2O \rightarrow SO_4^{2-} + 2H^+ + 4H_2$	0.4606
55	P	weathering of sedimentary P rock	$Ca_5(PO_4)_3(OH)$ (sediment) $\rightarrow 5Ca^{2+} + 3PO_4^{3-} + OH^-$	0.0214
56	P	soil to ocean P sediments	$5Ca^{2+} + 3PO_4^{3-} + OH^- \rightarrow Ca_5(PO_4)_3(OH)$	0.0187
57	P	P runoff	$PO_4^{3-} + H^+ \rightarrow HPO_4^{2-}$	0.0180
58	P	evaporation of soluble P	$3HPO_4^{2-} + 5Ca^{2+} + 3OH^- \rightarrow Ca_5(PO_4)_3(OH) + 2H_2O + H^+$	0.0003
59	P	deposition of soluble P	$Ca_5(PO_4)_3(OH) + 2H_2O + H^+ \rightarrow 3HPO_4^{2-} + 5Ca^{2+} + 3OH^-$	0.0005
60	P	deposition of insoluble P	$Ca_5(PO_4)_3(OH)$ (atmosphere) $\rightarrow$ $Ca_5(PO_4)_3(OH)$ (sediments)	0.0008
61	P	P particulate flux	$C_{100}H_{150}O_{80}N_4SP + 108O_2 + 3H^+ \rightarrow 100CO_2 + 76H_2O + 4NO_3^- + SO_4^{2-} + HPO_4^{2-}$	0.0420
62	P	formation of atmospheric P dust particles	$5Ca + OH + 3PO_4 \rightarrow Ca_5(PO_4)_3OH$	0.0031
63	P	dissolution of atmospheric P dust particles	$Ca_5(PO_4)_3OH \rightarrow 5Ca + OH + 3PO_4$	0.0021
64	P	P sedimentation	$6HPO_4^{2-} + 10Ca^{2+} + 8OH^- \rightarrow 2Ca_5(PO_4)_3(OH) + 6H_2O$	0.0019
65	P	sedimentary P rock formation	$Ca_5(PO_4)_3(OH)$ (marine sediments) $\rightarrow$ $Ca_5(PO_4)_3(OH)$ (uplifted sediments)	0.0214
66	H	transpiration	H_2O (liquid) $\rightarrow$ H_2O (gas)	3000.0587
67	H	evaporation from ocean	H_2O (liquid) $\rightarrow$ H_2O (gas)	43000.8411
68	H	precipitation to ocean	H_2O (gas) $\rightarrow$ H_2O (liquid)	39000.7629
69	H	precipitation to land	H_2O (gas) $\rightarrow$ H_2O (liquid)	11004.6122
70	H	evaporation from land	H_2O (liquid) $\rightarrow$ H_2O (gas)	4000.0782
71	H	uptake of H_2O	H_2O (liquid) $\rightarrow$ H_2O (liquid)	3000.0587
72	H	photooxidation of H_2	$H_2 + 0.5O_2 \rightarrow H_2O$	3.9864
73	H	river discharge	H_2O (liquid) $\rightarrow$ H_2O (liquid)	3955.4374

Table B.2 Biosphere Outputs From Processes (Continued)

	Cycle	Vensim Processes	1st Product: Chemical Species	Destination Reservoir	Mass (Pg)	2nd Product: Chemical Species	Destination Reservoir	Mass (Pg)
1	C	oxidation of land humus	$800CO_2$	Atmosphere CO_2	147.2686	$500H_2O$	Fresh water H_2O	37.6788
2	C	volcanic action	$100CO_2$	Atmosphere CO_2	0.0300	$700H_2O$	Fresh water H_2O	0.0861
3	C	land plant respiration	$750CO_2$	Atmosphere CO_2	329.8123	$750H_2O$	Fresh water H_2O	135.0124
4	C	tropospheric oxidation of CO	$2CO_2$	Atmosphere CO_2	5.4306			0.0000
5	C	release of CO_2	CO_2	Atmosphere CO_2	238.1705	H_2O	Ocean H_2O	97.4978
6	C	absorption of CO_2	HCO_3	Ocean NEC	359.2402	H^+	Ocean NEC	5.9345
7	C	gross land production	$C_{750}H_{1500}O_{750}N_{15}S_4P$	Land plants	362.1185	$782.5O_2$	O_2	396.1511
8	C	production of CO	100CO	Atmosphere NEC	0.2565	$125H_2O$	Ocean H_2O	0.2062
9	C	oxidation of CH_4	CO	Atmosphere NEC	3.6055	$2H_2O$	Atmosphere H_2O	4.6382
10	C	sorption of CO	$C_{800}H_{1000}O_{600}N_{32}S_4P$	Land humus	0.4118	$408O_2$	O_2	0.2582
11	C	production of CH_4	$150CH_4$	Atmosphere CH_4	0.4497	$100CO_2$	Atmosphere CO_2	0.8226
12	C	*land humus formation (p)*	$1.5C_{800}H_{1000}O_{600}N_{32}S_4P$	*Land humus*	78.1908	$300CO_2$	*Atmosphere* CO_2	33.0508
13	C	land consumption	$3C_{250}H_{500}O_{100}N_{50}P_3S$	Land consumers/decomposers	1.8989	SO_4	Soil	0.0103
14	C	gross marine production	$C_{100}H_{150}O_{80}N_4SP$	Marine plants	93.3889	$132.5O_2$	O_2	143.9222
15	C	marine plant respiration	$100HCO_3$	Ocean NEC	60.9623	$4NO_3$	Ocean NEC	2.4781
16	C	production of $CaCO_3$	$100CaCO_3$	Ocean NEC	9.1664	$4NO_3^-$	Ocean NEC	0.2272
17	C	marine humus formation (p)	$C_{100}H_{120}O_{80}N_3PS$	Marine humus	53.1906	$15H_2O$	Ocean H_2O	5.3100
18	C	marine consumption	$C_{100}H_{250}O_{140}N_{16}SP$	Marine consumers/decomposers	1.2592	$13O_2$	O_2	0.1316
19	C	land humus formation (c&d)	$C_{800}H_{1000}O_{600}N_{32}S_4P$	Land humus	0.6935	$200CO_2$	Atmosphere CO_2	0.2931
20	C	marine humus formation (c&d)	$C_{100}H_{120}O_{80}N_3PS$	Marine humus	0.6085	$13NO_3$	Ocean NEC	0.1812
21	C	coal formation	$6C_{130}H_{110}O_{10}N_2S$	Fossil fuels	0.0089	20CO	Atmosphere NEC	0.0004
22	C	transfer of land humus	$8C_{100}H_{120}O_{80}N_3PS$	Marine humus	0.9015	$8NO_3$	Ocean NEC	0.0207
23	C	oxidation of marine humus	$100HCO_3$	Ocean NEC	106.6842	$108H_2$	Atmosphere NEC	3.8068
24	C	kerogen formation	$C_{700}H_{1400}O_{1750}S_{28}P_7N_{14}$	Fossil fuels	2.3270	$3.5N_2$	Atmosphere N_2	0.0058
25	C	formation of limestone	$CaCO_3$	Sedimentary rock	2.9166			0.0000
26	C	weathering of limestone	HCO_3	Ocean NEC	1.7781	Ca^{2+}	Ocean NEC	1.1679
27	C	igneous rock formation	$C_{100}H_{1400}O_{1000}P_{32}S_{20}N_2$	Igneous rock	0.0014	$8SO_2$	Atmosphere NEC	0.0000
28	N	reduction of N_2O	$2N_2$	Atmosphere N_2	0.0300	O_2	O_2	0.0171
29	N	oxidation of N_2	$2N_2O$	Atmosphere N_2O	0.0236			0.0000
30	N	marine dentrification	N_2	Atmosphere N_2	0.0270	$6H_2O$	Ocean H_2O	0.1042
31	N	NOx formation by lightning	2NO	*Atmosphere NEC*	0.0107	$2NO_2$	*Atmosphere NEC*	0.0164
32	N	biological fixation by phytoplankton	$4C_{100}H_{150}O_{80}N_4SP$	Marine plants	1.9642	$406.5O_2$	O_2	2.3217
33	N	release of N_2 and N_2O	$400CO_2$	Atmosphere CO_2	3.1420	$300H_2O$	Ocean H_2O	0.9647
34	N	microbial production of N_2 and N_2O	$800CO_2$	Atmosphere CO_2	19.0454	$248H_2O$	Fresh water H_2O	2.4169
35	N	uptake of N_2 and N_2O	$C_{800}H_{1000}O_{600}N_{32}S_4P$	Land humus	8.5769	$635.5O_2$	O_2	8.3760
36	N	*photochemical oxidation of* N_2O	NO	Atmosphere NEC	0.0054	NO_2	Atmosphere NEC	0.0082
37	N	wet deposition of NOx	NO_3	Ocean NEC	0.0664			0.0000
38	N	acid rain	NO_3	Soil	0.0575			0.0000
39	N	microbial production of NH_3	$480CO_2$	Atmosphere CO_2	3.9590	$320CH_4$	Atmosphere CH_4	0.9620
40	N	uptake of NH_3 by soil	$C_{800}H_{1000}O_{600}N_{32}S_4P$	Land humus	2.5088	$364H_2O$	Fresh water H_2O	0.7901
41	N	uptake of NH_3 by ocean	NH_3 (dissolved)	Ocean NEC	0.1698			0.0000
42	N	N runoff	NO_3^- (ocean)	Ocean NEC	0.1417			0.0000
43	N	sedimentary N rock formation	NH_4^+	Sedimentary rock	0.0193	$1.5O_2$	O_2	0.0514
44	N	weathering of sedimentary N rock	NO_3	Ocean NEC	0.0221	$4H^+$	Ocean NEC	0.0014
45	S	release of H_2S	$48CH_4$	Atmosphere NEC	1.3211	$52CO_2$	Atmosphere CO_2	3.9265
46	S	ocean spray of SO_4	SO_2	Atmosphere NEC	0.0879	O_2	O_2	0.0439
47	S	uptake of SO_2 by ocean	SO_4^{2}	Ocean NEC	0.2876			0.0000
48	S	uptake of SO_2 by soil	SO_4^{2-}	Soil	0.3475			0.0000
49	S	ocean spray to land	SO_4^{2-}	Soil	0.0120			0.0000
50	S	S runoff	SO_4^{2-}	Ocean NEC	0.3982			0.0000
51	S	S sedimentation	SO_4^{2}	Marine sediments	0.1648			0.0000
52	S	sedimentary S rock formation	S_2^-	Sedimentary rock	0.0550	$2O_2$	O_2	0.1098
53	S	uplift and weathering of sedimentary S rock	SO_4^{2-}	Soil	0.1408			0.0000
54	S	H_2S dissolution	SO_4^{2-}	Ocean NEC	1.3800	$2H^+$	Ocean NEC	0.0290
55	P	*weathering of sedimentary P rock*	$5Ca^{2+}$	Soil	0.0462	$3PO_4^{3}$	Soil	0.0656
56	P	soil to ocean P sediments	$Ca_5(PO_4)_3(OH)$	Marine sediments	0.1011			0.0000
57	P	P runoff	HPO_4^{2}	Ocean NEC	0.0558			0.0000
58	P	evaporation of soluble P	$Ca_5(PO_4)_3(OH)$	Atmosphere NEC	0.0016	$2H_2O$	Atmosphere H_2O	0.0001
59	P	deposition of soluble P	$3HPO_4^{2}$	Ocean NEC	0.0015	$5Ca^{2+}$	Ocean NEC	0.0011
60	P	deposition of insoluble P	$Ca_5(PO_4)_3(OH)$	Marine sediments	0.0043			0.0000
61	P	P particulate flux	$100CO_2$	Atmosphere CO_2	5.9676	$76H_2O$	Ocean H_2O	1.8566
62	P	formation of atmospheric P dust particles	$Ca_5(PO_4)_3OH$	Atmosphere NEC	0.0168			0.0000
63	P	dissolution of atmospheric P dust particles	5Ca	Soil	0.0045	OH	Soil	0.0004
64	P	P sedimentation	$2Ca_5(PO_4)_3(OH)$	Marine sediments	0.0103	$6H_2O$	Ocean H_2O	0.0011
65	P	sedimentary P rock formation	$Ca_5(PO_4)_3(OH)$	Sedimentary rock	0.1157			0.0000
66	H	transpiration	H_2O	Atmosphere H_2O	26,810.0482			0.0000
67	H	evaporation from ocean	H_2O	Atmosphere H_2O	384,277.3578			0.0000
68	H	precipitation to ocean	H_2O	Ocean H_2O	348,530.6268			0.0000
69	H	precipitation to land	H_2O	Fresh water H_2O	98,342.8045			0.0000
70	H	evaporation from land	H_2O	Atmosphere H_2O	35,746.7310			0.0000
71	H	uptake of H_2O	H_2O	Land plants	26,810.0482			0.0000
72	H	photooxidation of H_2	H_2O	Atmosphere H_2O	35.6241			0.0000
73	H	river discharge	H_2O	Ocean H_2O	35,347.7974			0.0000

Table B.2 Biosphere Outputs From Processes (Continued)

	Cycle	Vensim Processes	3rd Product			4th Product			5th Product		
			Chemical Species	Destination Reservoir	Mass (Pg)	Chemical Species	Destination Reservoir	Mass (Pg)	Chemical Species	Destination Reservoir	Mass (Pg)
1	C	oxidation of land humus	$32NO_3$	Soil	8.3000	PO_4^{3-}	Soil	0.3972	$4SO_4^{2-}$	Soil	1.6072
2	C	volcanic action	$32 PO_4^{3-}$	Soil	0.0207	$20SO_2$	Atmosphere NEC	0.0087	N_2	Atmosphere N_2	0.0002
3	C	land plant respiration	$15NO_3^-$	Soil	9.2941	$4SO_4^{2-}$	Soil	3.8393	PO_4^{3-}	Soil	0.9489
4	C	tropospheric oxidation of CO			0.0000			0.0000			0.0000
5	C	release of CO_2			0.0000			0.0000			0.0000
6	C	absorption of CO_2			0.0000			0.0000			0.0000
7	C	gross land production			0.0000			0.0000			0.0000
8	C	production of CO	$16NO_3$	Ocean NEC	0.0909	SO_4	Ocean NEC	0.0088	HPO_4	Ocean NEC	0.0088
9	C	oxidation of CH_4			0.0000			0.0000			0.0000
10	C	sorption of CO			0.0000			0.0000			0.0000
11	C	production of CH_4	$50NH_3$	Atmosphere NEC	0.1592	$3PO_4$	Soil	0.0533	SO_4	Soil	0.0180
12	C	land humus formation (p)	$750H_2O$	Fresh water H_2O	33.8244	$0.5PO_4$	Soil	0.1189	$2SO_4$	Soil	0.4809
13	C	land consumption	$441.5O_2$	O_2	1.5075			0.0000			0.0000
14	C	gross marine production	H^+	Ocean NEC	0.0342			0.0000			0.0000
15	C	marine plant respiration	HPO_4^{3-}	Ocean NEC	0.9589	SO_4^{2-}	Ocean NEC	0.9597	$25H_2O$	Ocean H_2O	4.4999
16	C	*production of $CaCO_3$*	HPO_4^{3-}	Ocean NEC	0.0879	SO_4^{2-}	Ocean NEC	0.0880	$75H_2O$	Ocean H_2O	1.2375
17	C	marine humus formation (p)	NO_3	Ocean NEC	1.2184			0.0000			0.0000
18	C	marine consumption			0.0000			0.0000			0.0000
19	C	land humus formation (c&d)	$168NO_3$	Soil	0.3469	$500H_2O$	Fresh water H_2O	0.3000	$11PO_4$	Soil	0.0348
20	C	marine humus formation (c&d)	$65H_2O$	Ocean H_2O	0.2632			0.0000			0.0000
21	C	coal formation	$170H_2O$	Fresh water H_2O	0.0024	$10N_2$	Atmosphere N_2	0.0002	$177O_2$	O_2	0.0044
22	C	transfer of land humus	$20H_2O$	Ocean H_2O	0.0150	$7H^+$	Soil	0.0003			0.0000
23	C	oxidation of marine humus	HPO_4^{3-}	Ocean NEC	1.6781	H_2S	Atmosphere NEC	0.5958	$3NH_3$	Ocean NEC	0.8935
24	C	kerogen formation			0.0000			0.0000			0.0000
25	C	formation of limestone			0.0000			0.0000			0.0000
26	C	weathering of limestone			0.0000			0.0000			0.0000
27	C	igneous rock formation	$6N_2$	Atmosphere N_2	0.0000	$600CO_2$	Atmosphere CO_2	0.0019	$25H^+$	Ocean NEC	0.0000
28	N	reduction of N_2O			0.0000			0.0000			0.0000
29	N	oxidation of N_2			0.0000			0.0000			0.0000
30	N	marine denitrification			0.0000			0.0000			0.0000
31	N	NOx formation by lightning			0.0000			0.0000			0.0000
32	N	biological fixation by phytoplankton	$4H^+$	Ocean NEC	0.0007			0.0000			0.0000
33	N	release of N_2 and N_2O	$4SO_4$	Ocean NEC	0.0686	$4HPO_4$	Ocean NEC	0.0685	N_2O	Atmosphere N_2O	0.0079
34	N	microbial production of N_2 and N_2O	$13N_2$	Atmosphere N_2	0.1970	$3N_2O$	Atmosphere N_2O	0.0714	PO_4^{3-}	Soil	0.0514
35	N	uptake of N_2 and N_2O			0.0000			0.0000			0.0000
36	N	photochemical oxidation of N_2O			0.0000			0.0000			0.0000
37	N	wet deposition of NOx			0.0000			0.0000			0.0000
38	N	acid rain			0.0000			0.0000			0.0000
39	N	microbial production of NH_3	$32NH_3$	Atmosphere NEC	0.1022	$172H_2$	Atmosphere NEC	0.0650	$4H_2S$	Atmosphere NEC	0.0255
40	N	uptake of NH_3 by soil			0.0000			0.0000			0.0000
41	N	uptake of NH_3 by ocean			0.0000			0.0000			0.0000
42	N	N runoff			0.0000			0.0000			0.0000
43	N	sedimentary N rock formation			0.0000			0.0000			0.0000
44	N	weathering of sedimentary N rock			0.0000			0.0000			0.0000
45	S	release of H_2S	H_2S	Atmosphere NEC	0.0585	$4NH_3$	Atmosphere NEC	0.1169	PO_4^{3-}	Ocean NEC	0.1629
46	S	ocean spray of SO_4			0.0000			0.0000			0.0000
47	S	*uptake of SO_2 by ocean*			0.0000			0.0000			0.0000
48	S	uptake of SO_2 by soil			0.0000			0.0000			0.0000
49	S	ocean spray to land			0.0000			0.0000			0.0000
50	S	S runoff			0.0000			0.0000			0.0000
51	S	S sedimentation			0.0000			0.0000			0.0000
52	S	sedimentary S rock formation			0.0000			0.0000			0.0000
53	S	uplift and weathering of sedimentary S rock			0.0000			0.0000			0.0000
54	S	H_2S dissolution	$4H_2$	Atmosphere NEC	0.1159			0.0000			0.0000
55	P	weathering of sedimentary P rock	OH^-	Soil	0.0039			0.0000			0.0000
56	P	soil to ocean P sediments			0.0000			0.0000			0.0000
57	P	P runoff			0.0000			0.0000			0.0000
58	P	evaporation of soluble P	H^+	Ocean NEC	0.0000			0.0000			0.0000
59	P	deposition of soluble P	$3OH^-$	Ocean NEC	0.0003			0.0000			0.0000
60	P	deposition of insoluble P			0.0000			0.0000			0.0000
61	P	P particulate flux	$4NO_3^-$	Ocean NEC	0.3363	SO_4^{2-}	Ocean NEC	0.1303	HPO_4^{2-}	Ocean NEC	0.1301
62	P	formation of atmospheric P dust particles			0.0000			0.0000			0.0000
63	P	dissolution of atmospheric P dust particles	$3PO_4$	Soil	0.0064			0.0000			0.0000
64	P	P sedimentation			0.0000			0.0000			0.0000
65	P	sedimentary P rock formation			0.0000			0.0000			0.0000
66	H	transpiration			0.0000			0.0000			0.0000
67	H	evaporation from ocean			0.0000			0.0000			0.0000
68	H	precipitation to ocean			0.0000			0.0000			0.0000
69	H	*precipitation to land*			0.0000			0.0000			0.0000
70	H	evaporation from land			0.0000			0.0000			0.0000
71	H	uptake of H_2O			0.0000			0.0000			0.0000
72	H	photooxidation of H_2			0.0000			0.0000			0.0000
73	H	river discharge			0.0000			0.0000			0.0000

Table B.2 Biosphere Outputs From Processes (Continued)

	Cycle	Vensim Processes	6th Product Chemical Species	6th Product Destination Reservoir	6th Product Mass	7th Product Chemical Species	7th Product Destination Reservoir	7th Product Mass	Total Product Flux Mass
					Pg			Pg	Pg
1	C	oxidation of land humus			0.0000			0.0000	195.2518
2	C	volcanic action			0.0000			0.0000	0 1458
3	C	land plant respiration			0.0000			0.0000	478.9071
4	C	tropospheric oxidation of CO			0 0000			0.0000	5 4306
5	C	release of CO_2			0 0000			0 0000	335.6683
6	C	*absorption of CO_2*			*0.0000*			*0 0000*	*365 1747*
7	C	gross land production			0.0000			0 0000	758 2696
8	C	production of CO			0 0000			0 0000	0 5712
9	C	oxidation of CH_4			0 0000			0 0000	8.2437
10	C	sorption of CO			0 0000			0 0000	0 6699
11	C	production of CH_4	4 SO_2	O_2	0 0269			0 0000	1 5296
12	C	land humus formation (p)			0 0000			0 0000	145 6658
13	C	land consumption			0 0000			0 0000	3 4167
14	C	gross manne production			0.0000			0 0000	237 3453
15	C	marine plant respiration			0 0000			0 0000	69 8590
16	C	production of $CaCO_3$			0 0000			0 0000	10 8069
17	C	marine humus formation (p)			0 0000			0 0000	59 7190
18	C	marine consumption			0 0000			0 0000	1 3909
19	C	land humus formation (c&d)			0 0000			0 0000	1 6683
20	C	marine humus formation (c&d)			0 0000			0 0000	1 0530
21	C	coal formation	PO_4	Soil	0 0001			0 0000	0 0164
22	C	transfer of land humus			0 0000			0 0000	0 9375
23	C	oxidation of marine humus			0 0000			0 0000	113 6583
24	C	kerogen formation			0 0000			0 0000	2 3328
25	C	formation of limestone			0 0000			0 0000	2 9166
26	C	weathering of limestone			0.0000			0 0000	2 9460
27	C	igneous rock formation			0 0000			0 0000	0 0034
28	N	reduction of N_2O			0.0000			0 0000	0 0471
29	N	oxidation of N_2			0 0000			0 0000	0 0236
30	N	marine dentrification			0 0000			0 0000	0 1312
31	N	NOx formation by lightning			0 0000			0 0000	0 0271
32	N	biological fixation by phytoplankton			0 0000			0 0000	4 2866
33	N	release of N_2 and N_2O	N_2	Atmosphere N_2	0 0350			0 0000	4 2866
34	N	microbial production of N_2 and N_2O	4SO_4	Soil	0 2079	504H⁺	Soil	0 2748	22 2648
35	N	uptake of N_2 and N_2O			0 0000			0 0000	16 9529
36	N	photochemical oxidation of N_2O			0 0000			0 0000	0 0136
37	N	wet deposition of NOx			0.0000			0 0000	0 0664
38	N	acid rain			0 0000			0 0000	0 0575
39	N	microbial production of NH_3	PO_4	Soil	0 0178			0 0000	5 1315
40	N	uptake of NH_3 by soil			0 0000			0 0000	3 2988
41	N	uptake of NH_3 by ocean			0 0000			0 0000	0 1698
42	N	N runoff			0 0000			0.0000	0 1417
43	N	*sedimentary N rock formation*			*0 0000*			*0 0000*	*0 0707*
44	N	weathering of sedimentary N rock			0 0000			0 0000	0 0236
45	S	release of H_2S			0 0000			0 0000	5.5860
46	S	ocean spray of SO_4			0 0000			0 0000	0 1318
47	S	uptake of SO_2 by ocean			0 0000			0 0000	0 2876
48	S	uptake of SO_2 by soil			0 0000			0 0000	0 3475
49	S	ocean spray to land			0 0000			0 0000	*0 0120*
50	S	S runoff			0 0000			0 0000	0 3982
51	S	S sedimentation			0 0000			0 0000	0 1648
52	S	sedimentary S rock formation			0 0000			0 0000	0 1648
53	S	uplift and weathering of sedimentary S rock			0.0000			0 0000	0 1408
54	S	H_2S dissolution			0.0000			0 0000	1 5249
55	P	weathering of sedimentary P rock			0 0000			0 0000	0 1157
56	P	soil to ocean P sediments			0 0000			0 0000	0 1011
57	P	P runoff			0 0000			0.0000	0 0558
58	P	evaporation of soluble P			0 0000			0 0000	0 0017
59	P	deposition of soluble P			0 0000			0 0000	0 0029
60	P	deposition of insoluble P			0 0000			0 0000	0 0043
61	P	P particulate flux			0 0000			0 0000	8 4209
62	P	formation of atmospheric P dust particles			0 0000			0 0000	0 0168
63	P	dissolution of atmospheric P dust particles			0 0000			0 0000	0 0114
64	P	P sedimentation			0 0000			0 0000	0 0114
65	P	sedimentary P rock formation			0.0000			0 0000	0 1157
66	H	transpiration			0 0000			0 0000	26,810 0482
67	H	evaporation from ocean			0.0000			0 0000	384,277 3578
68	H	precipitation to ocean			0.0000			0.0000	348,5306268
69	H	precipitation to land			0 0000			0.0000	98,342.8045
70	H	evaporation from land			0 0000			0 0000	35,746 7310
71	H	uptake of H_2O			0 0000			0 0000	26,810 0482
72	H	photooxidation of H_2			0 0000			0 0000	35 6241
73	H	river discharge			0 0000			0 0000	35,347 7974

B.2.2 Global Reservoirs

Reservoir masses for key chemical species transformed by ecological processes are recorded below in Tables B.3 to B.7. These Tables show the (approximate) quantities (columns) of C, H, P, S, and N in various reservoirs (rows). Where possible estimates from key studies are recorded providing an indication of the range of published estimates. The final column in each Table reports the global reservoir mass estimate utilised here and, in turn, by McDonald and Patterson (2005), in development of a global dynamic biogeochemical cycling model. A valuable cross-check between the static mass fluxes utilised by Patterson (2005), and the reservoir mass established in this thesis, is the calculation of residence times[285] – and in turn, comparison of these times with literature based estimates. Atmospheric water, for example, is known to have a residence time of approximately 10.2 days (Bowen, 1979). Dividing the mass of the global atmospheric water reservoir, 1,436 Pg H (row entitled Atmosphere H2O[286] of Table B.4), by the annual H flux leaving the atmosphere, 50,005[287] Pg H, gives an estimated residence time of 0.028 years or approximately 10.4 days – a result comparable with the independent literature estimate. Other reservoir and flux rates were tested in a similar fashion.

Estimation of the key chemical species reservoirs, like their associated fluxes, are difficult to obtain with estimates varying widely (see, for example, Lerman *et al.* (1989), Mackenzie *et al.* (1993), den Elzen *et al.* (1995), Ayres (1996), and Smil (2002)).

[285] For element x, residence time, Tx, may be defined mathematically as Tx = Mx / Rx, where Mx is the reservoir mass and Rx the reservoir's total annual outflow rate (Bowen, 1979).
[286] As the Vensim® modelling language does not permit the use of subscripts in its stock descriptions, the conventions of the modelling language, rather than those of chemistry, have been adopted here for consistency.
[287] Refer to Table B.1 – summation of rows 66, 67 and 70 of column entitled Marker Element.

Table B.3 Global Carbon Reservoirs

	Bowen (1979)	Schlesinger (1991)	Holmen (1992)	Mackenzie *et al*. (1993)	Den Elzen *et al*. (1995)	Ayres (1996)	This Study
	Pg C	Pg C	Pg C	Pg C	Pg C	Pg C	Pg C
Atmosphere							
Atmosphere CO2	660	720	747	739	753	730	738
Atmosphere CH4	3.30	3.22		3.51	3.00		3.41
Atmosphere NEC							
- CO	0.23	0.25		0.23			0.23
Terrestrial Biosphere							
Land Consumers/Decomposers	0.90						0.90
Land Plants	830	560	480 to 1,080	598	610		740
Land Humus	2,500(1)	1,500		1,420	1,580		1,500
Marine Biosphere							
Ocean NEC							
- $CaCO_3$ (Calcium carbonate)	1,290		1,030	1,057	770		1,037
- Surface Sea HCO_3^{2-} (Bicarbonate)	750		700		1,020		823
- Deep Sea HCO_3^{2-} (Bicarbonate)	37,300		37,900	38,432	38,100		37,933
Marine Consumers/Decomposers	0.9						0.15
Marine Plants	1.75						3.25
Marine Humus	1,000(2)						1,000
Lithosphere							
Fossil Fuels							
- $C_{225}H_{450}S$ (Petroleum)	4,300						4,300
- $C_{130}H_{110}O_{10}N_2S$ (Coal)	3,000,000						3,000,000
- $C_{700}H_{1400}O_{1750}S_{28}P_7N_{14}$ (Oil Shale)	15,000,000						15,000,000
- CH_4 (Natural Gas)	38,700						38,700
Igneous Rock	10,000,000						10,000,000
Sedimentary Rock							
- CO_3^{2-} from $CaCO_3$	78,000,000		70,000,000	62,452,000			70,150,667

Notes:

1. Includes inorganic C in the soil.
2. This value is highly uncertain. Bowen (1979, p.70) states: "taken from estimates by Skirrow (1975) and Williams (1975)". Whittaker (1975) gives a value greater by a factor of 10, Wedepohl (1969) gives a range from 280 – 3800.

Table B.4 Global Hydrogen Reservoirs

	Leopold (1974) in Murray (1992)	Bowen (1979)	Schlesinger (1991)	Shiklomanov (1993)	This Study
	Pg H	Pg H	Pg H	Pg H	Pg H
Atmosphere					
Atmosphere NEC					
- H_2		0.26	0.18		0.22
Terrestrial Biosphere					
Land Plants					
- H_2O		92		125	109
Hydrosphere					
Atmosphere H2O	1,455	1,400	1,450	1,440	1,436
Fresh Water H2O(1)					
- Lakes	13,988			10,183	12,085
- Rivers	145	140		237	174
- Groundwater					
- Groundwater	895,204			1,178,313	
- Soil moisture	7,497			1,846	
Ocean H2O					
- Ocean	148,800,000	152,000,000	151,100,000	149,700,000	150,400,000
- Lakes Saline	11,638			9,556	10,597

Notes:
1. Excludes glaciers, permanent snow, ice and water in the lithosphere.

Table B.5 Global Phosphorus Reservoirs

	Schlesinger (1991)	Jahnke (1992)	Mackenzie *et al*. (1993)	Den Elzen *et al*. (1995)	Ayres (1996)	This Study
	Pg P	Pg P	Pg P	Pg P	Pg P	Pg P
Atmosphere						
Atmosphere NEC						
- $Ca_5(PO_4)_3(OH)$	0.00003	0.00003	0.00003			0.00003
Terrestrial Biosphere						
Land Humus			12.4			12
Soil						
- PO_4^{3-} (Phosphate)	256	200	200 to 402			250
Marine Biosphere						
Ocean NEC						
- Total Ocean						
- HPO_4^{2-} (Monohydrogen phosphate)	80.00	89.81	81 to 92; 80.52	89.81	80.00	84
- Surface Sea						
- HPO_4^{2-} (Monohydrogen phosphate)		2.71	8.35	2.71		4.59
- Deep Sea						
- HPO_4^{2-} (Monohydrogen phosphate)		87.1	91.98	87.1		89
Marine Humus	0.65			0.65		0.65
Marine Sediments						
- $Ca_5(PO_4)_3(OH)$ (Calcium phosphate)	840,000			840,000	840,000	840,000
Lithosphere						
Sedimentary Rock						
- $Ca_5(PO_4)_3(OH)$ (Calcium phosphate)	160				110	135

Table B.6 Global Sulphur Reservoirs

	Bowen (1979)	Schlesinger (1991)	Charlson *et al*. (1992)	Mackenzie *et al*. (1993)	Den Elzen *et al*. (1995)	Ayres (1996)	This Study
	Pg S	Pg S		Pg S	Pg S	Pg S	Pg S
Atmosphere							
Atmosphere NEC							
- H_2S	0.020	0.001		0.001			0.002
- SO_2	0.020	0.002		0.001		0.005	0.005
Terrestrial Biosphere							
Land Humus				96	300		198
Soil							
- SO_4^{2-} (Sulfate)	88						88
Marine Biosphere							
Ocean NEC							
- SO_4^{2-} (Sulfate)	1,260,000	1,280,000	1,300,000	1,250,340	1,300,000	1,300,000	1,281,723
Marine Plants		0.024					0.024
Marine Sediments							
- SO_4^{2-} (Sulfate)			300,000		300,000	300,000	300,000
Lithosphere							
Fossil Fuels							
- $C_{225}H_{450}S$ (Petroleum)	75						75
- $C_{130}H_{110}O_{10}N_2S$ (Coal)	37,000						37,000
Igneous Rock	5,500,000	5,150,000					5,325,000
Sedimentary Rock							
- S^{2-}	2,500,000	2,650,000					2,575,000

Table B.7 Global Nitrogen Reservoirs

	McElroy *et al.* (1976) in Jaffe (1992)	Soderland and Svensson (1976) in Jaffe (1992)	Bowen (1979)	Stedman and Shetter (1983) in Jaffe (1992)	Schlesinger (1991)	Mackenzie *et al.* (1993)	Den Elzen *et al.* (1995)	This Study
	Pg N	Pg N	Pg N	Pg N	Pg N	Pg N	Pg N	Pg N
Atmosphere								
Atmosphere N2	4,000,000	3,900,000	3,900,000	3,900,000	3,800,000	3,922,800	3,800,000	3,870,467
Atmosphere N2O	1.10	1.30	1.30	1.40	1.46	1.50	1.50	1.41
Atmosphere NEC								
- NH_3		0.001	0.026	0.000	0.025	0.002	0.000	0.008
- NO_xs		0.001 to 0.004	0.004	0.0002	0.002	0.002	0.0006	0.001
Terrestrial Biosphere								
Land Consumers/Decomposers		0.20				0.20		0.20
Land Plants	10	11 to 14				9.81		10.77
Land Humus					95	2.61 to 391; 34	95	75
Soil								
- NO_3 (Nitrate)	60	300	250			290		280
Marine Biosphere								
Ocean NEC								
- Total Ocean								
- NO_3 (Nitrate)		570	770			570 to 720		662
- NH_3 (Ammonia)			21			53		37
- Surface Sea NO_3 (Nitrate)						4.38		4.38
- Deep Sea NO_3 (Nitrate)						715		715
Marine Consumers/Decomposers		0.17				0.17		0.17
Marine Plants		0.30				0.29	0.30	0.30
Marine Humus		3.00				9.95	3.24	5.40
Lithosphere								
Fossil Fuels								
- $C_{130}H_{110}O_{10}N_2S$ (Coal)			56,000					56,000
Igneous Rock			520,000					520,000
Sedimentary Rock								
- NH_4^+			1,499,320			1,000,314		1,249,817

B.3 Description of Stocks, Flows and Converters in the GBCM

In this Section the stocks, flows and converters utilised within the GBCM are described. The model's variables are described in italics with subscripts denoting variables with arrayed dimensions. Furthermore, it should be noted that the Vensim® naming conventions are followed, namely: (1) all stocks begin with capital letters, and (2) all flows and converters begin with lower case letters. To aid the reader in the comprehension of the model full variable names are utilised where possible.

Stocks

The GBCM consists of 21 stocks which may have been broadly categorised as follows: (1) atmosphere stocks (*Atmosphere* $CO2_e$, *Atmosphere* $CH4_e$, *Atmosphere* $N2_e$, *Atmosphere* $N2O_e$, *Atmosphere* NEC_e), terrestrial stocks (*Land Consumers and* $Decomposers_e$, *Land* $Plants_e$, *Land* $Humus_e$, $Soil_e$), marine stocks (*Marine Consumers and* $Decomposers_e$, *Marine* $Plants_e$, *Marine* $Humus_e$, *Marine* $Sediment_e$, *Ocean* NEC_e), hydrosphere stocks (*Atmosphere* $H2O_e$, *Freshwater* $H2O_e$, *Ocean* $H2O_e$), lithosphere stocks (*Sedimentary* $Rocks_e$, *Fossil* $Fuels_e$, *Igneous* $Rock_e$) and $Oxygen_e$ stock. Each stock has the dimension *e*, where *e* is a set of the following chemical elements: C, H, N, O, P, S, Ca.

Flows

Marker Element Flows

The GBCM is comprised of 73 'marker element' flows representing the global ecological processes. The flows, as per Chapter 7, are grouped according to the carbon, hydrological, phosphorus, sulphur and nitrogen cycles. These flows are designated as 'marker element' flows as they record only the flow of the element represented by the cycle in which they reside. The *gross land* $production_e$ ecological process, for example, resides in the carbon cycle – therefore it records only the flow of carbon. Each marker flow, like its donor or receptor stock, has the dimension *e*.

Non-Marker Element Flows

Once the marker element flows have been established for a particular ecological process it is then possible, using chemical stoichiometry, to determine all 'non-marker' (i.e. by-product) element flows associated with that process.[288] The GBCM consists of 42 non-marker flows i.e. one inflow and one outflow for each stock. Each non-marker flow, like each marker flow, has the dimension *e*.

Converters

The flow rate of each marker element outflow in the GBCM is governed by the size of its donor stock and a converter representing the annual average outflow rate of the marker element within the stock. This requires a total of 73 converters. The calculation of non-marker element flows requires an additional 42 converters – one for each stock inflow and outflow. Generally speaking, converter names are abbreviations of the flows they represent with a 'rt' (rate) suffix. The converter $toco\ rt_e$, for example, is an abbreviation of the $tropospheric\ oxidation\ of\ CO_e$ flow. Once again each converter has the dimension *e*.

B.4 GBCM Mathematical Description

The GBCM, unlike the ARDEEM, cannot easily be split into modules. This is a consequence of the highly integrated nature of the model. The stock of marine plants, for example, not only features in the carbon cycle, but is also in the phosphorus, sulphur and nitrogen cycles. Such interdependence in the GBCM is perhaps best expressed by counting the number of feedback loops that exist for each stock – 18 of the 21 stocks have more than 20,000 feedback loops, and 15 stocks have more than 30,000 feedback loops. This high level of interconnectivity prohibits the separation of the GBCM into modules for mathematical description. The mathematics of the GBCM is instead described below using $CO2\ Atmosphere_e$ stock as an example. A complete set of finite difference equations is provided at the end of this Appendix.

$$Atmosphere\ CO2_e(t + dt) = Atmosphere\ CO2_e(t) + (atmos\ CO2\ from\ op_e + land\ plant\ respiration_e + oxidation\ of\ land\ humus_e + release\ of\ CO2_e + tropospheric\ oxidation\ of\ CO_e + volcanic\ action_e - absorption\ of\ CO2_e - atmos\ CO2\ for\ op_e - gross\ land\ production_e) \times dt$$

where:

$$atmos\ CO2\ from\ op_e = \sum_{aco2rp=1}^{m} \left(atmos\ CO2\ nmrsm_{aco2rp,e} \times \sum_{e=1}^{n} \left(\{atmos\ CO2\ nmrsm\ processes_{aco2rp,e}\} \right) \right)$$

[288] This includes the physical flow of other elements of the chemical species in which the marker element may reside. If carbon is the marker element and it resides in the compound CO_2 then the estimation of non-marker flows would include the O_2 component of the CO_2 compound.

land plant respiration$_e$	$= Land\ Plant_e(t) \times lpr\ rt_e$
oxidation of land humus$_e$	$= Land\ Humus_e(t) \times olh\ rt_e$
release of CO2$_e$	$= Ocean\ NEC_e(t) \times rco2\ rt_e$
tropospheric oxidation of CO$_e$	$= Atmosphere\ NEC_e(t) \times toco\ rt_e$
volcanic action$_e$	$= Igneous\ Rock_e(t) \times va\ rt_e$
absorption of CO2$_e$	$= Atmosphere\ CO2_e(t) \times aco2\ rt_e$
atmos CO2 for op$_e$	$= \sum_{aco2dp=1}^{m} (atmos\ CO2\ nmdsm_{aco2dp,e} \times \sum_{e=1}^{n} (\{atmos\ CO2\ nmdsm\ processes_{aco2dp,e}\}))$
gross land production$_e$	$= Atmosphere\ CO2_e(t) \times glp\ rt_e$

The *Atmosphere CO2*$_e$ stock records the level of atmospheric CO_2. It is calculated by adding inflows to, and subtracting outflows from, the *Atmosphere CO2*$_e$ stock value at ($t - dt$): (1) marker element inflows – *land plant respiration*$_e$, *oxidation of land humus*$_e$, *release of CO2*$_e$, *tropospheric oxidation of CO*$_e$, and *volcanic action*$_e$; (2) non-marker element inflow – *atmos CO2 from op*$_e$, (3) marker element outflows – *absorption of CO2*$_e$, and *gross land production*$_e$, and (4) non-marker element outflow – *atmos CO2 for op*$_e$. Marker element flows are governed by the size of the donor stock and a converter representing the annual average outflow rate of the marker element within each stock.[289] The annual release of CO_2 into the atmosphere from *land plant respiration*$_e$ process (measured in kt C), for example, is calculated by multiplying *Land Plant*$_e$ by the annual average outflow rate of *lpr rt*$_e$.

The calculation of the non-marker inflow, *atmos CO2 from op*$_e$, and non-marker outflow, *atmos CO2 for op*$_e$, is more complicated. Consider, for example, the non-marker outflow:

$$atmos\ CO2\ for\ op_e = \sum_{aco2dp=1}^{m} (atmos\ CO2\ nmdsm_{aco2dp,e} \times \sum_{e=1}^{n} (\{atmos\ CO2\ nmdsm\ processes_{aco2dp,e}\}))$$

where:

$\{atmos\ CO2\ nmdsm\ processes_{aco2dp,e}\}$ = all non-marker processes requiring CO_2 as a chemical reactant. The parentheses '{}' are used to denote an array of marker element flows as per the *aco2dp* set and element *e*

$atmos\ CO2\ nmdsm_{aco2dp,e}$ = non-marker atmospheric CO_2 utilised by process *aco2dp* by element *e*

[289] It is assumed that the residence time of a unit of the element within the donor stock, calculated as the reciprocal of the annual average outflow rate, remains constant over time.

aco2dp = *biological fixation by phytoplankton*$_e$, *uptake of N2 and N2O*$_e$, *uptake of NH3 by soil*$_e$, *absorption of CO2*$_e$, and *gross land production*$_e$

The non-marker outflow, *atmos CO2 for op*$_e$, is therefore comprised of a series of multiplications and summations that maintain the stoichiometric relationships between marker and non-marker element values on the reactant side of the chemical equations representing each ecological process. By contrast, the non-marker inflow, *atmos CO2 from op*$_e$, maintains the stoichiometric relationships between marker and non-marker element values on the product side of the chemical equations.

Vensim® system dynamics influence diagrams for each cycle are given in Figures B.1 to B.5. These diagrams show only marker element flows for the sake of clarity – all non-marker element flows have been hidden. Each diagram may therefore be thought of as a partial view of the system. Since the flows have already been described in detail in Patterson (2005) no further explanation is provided here.

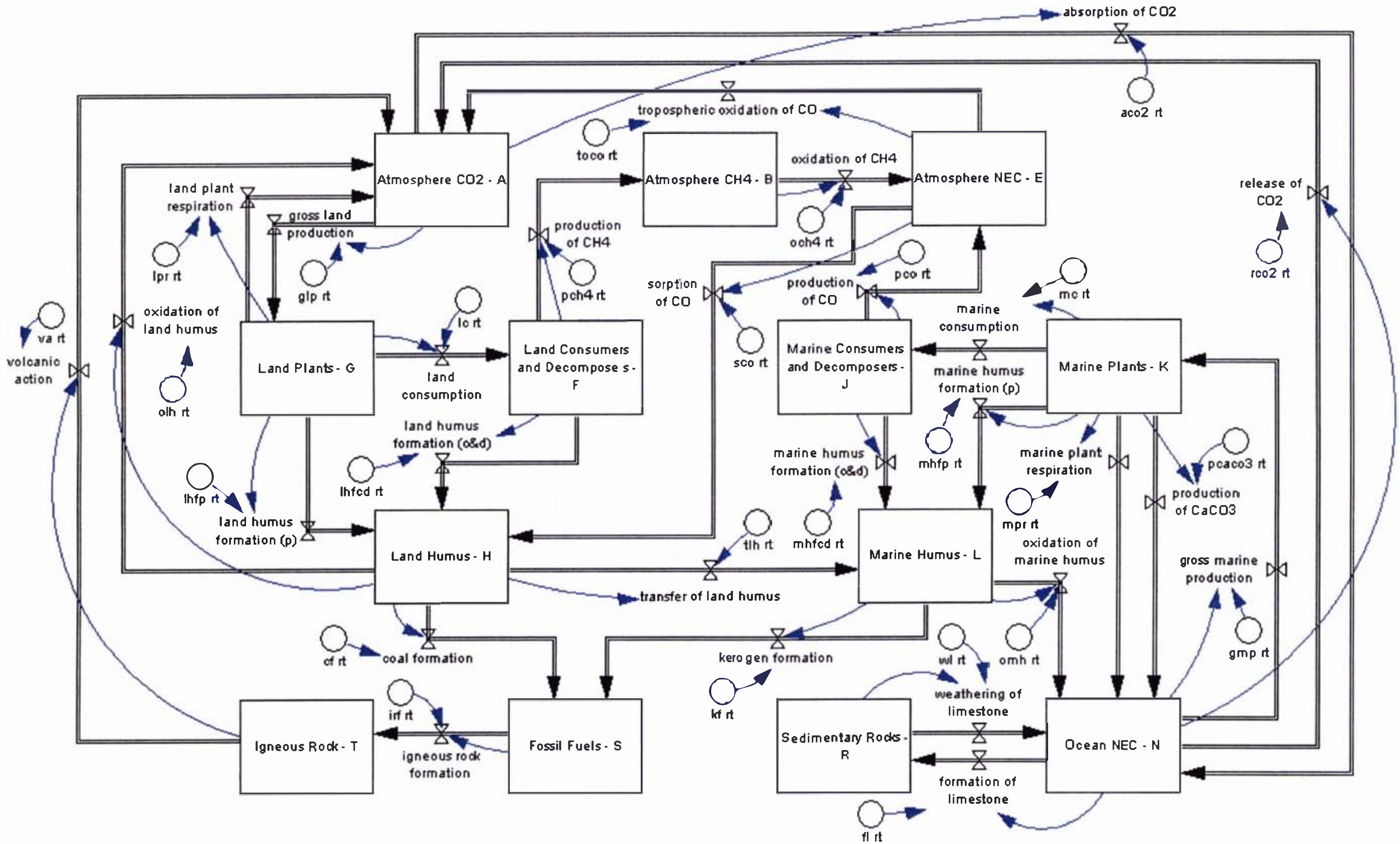


Figure B.1 **Carbon Cycle Influence Diagram**

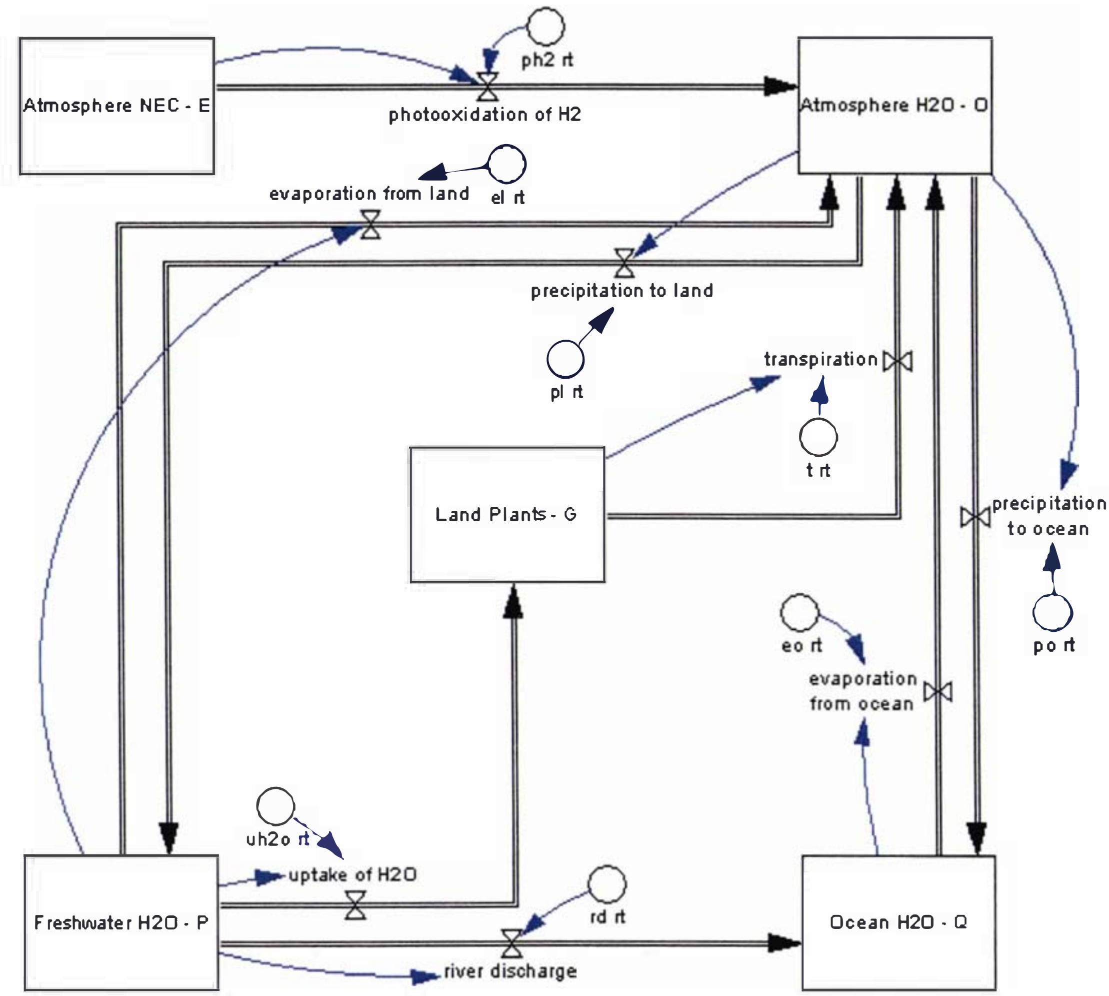


Figure B.2 Hydrological Cycle Influence Diagram

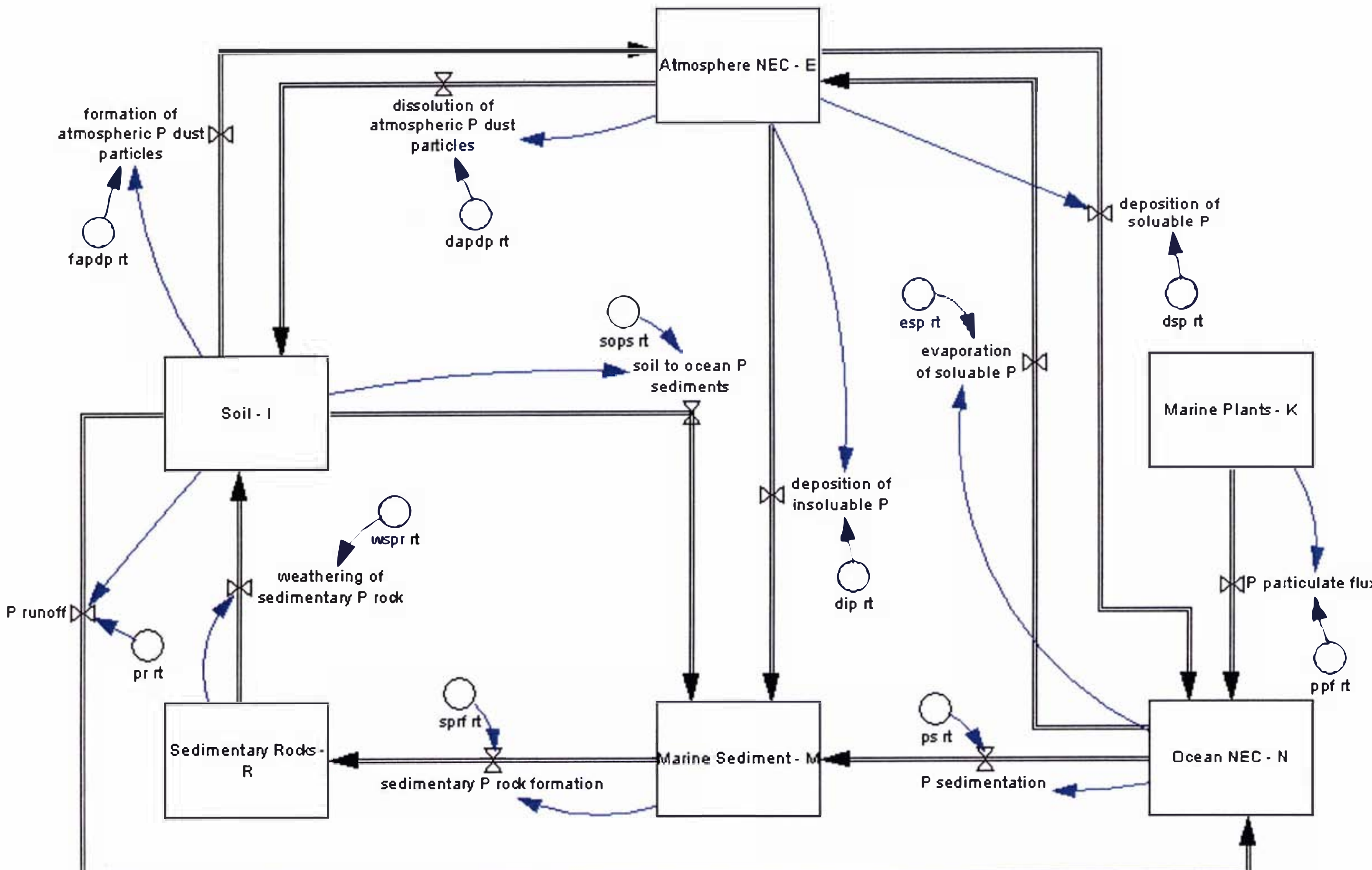


Figure B.3 **Phosphorus Cycle Influence Diagram**

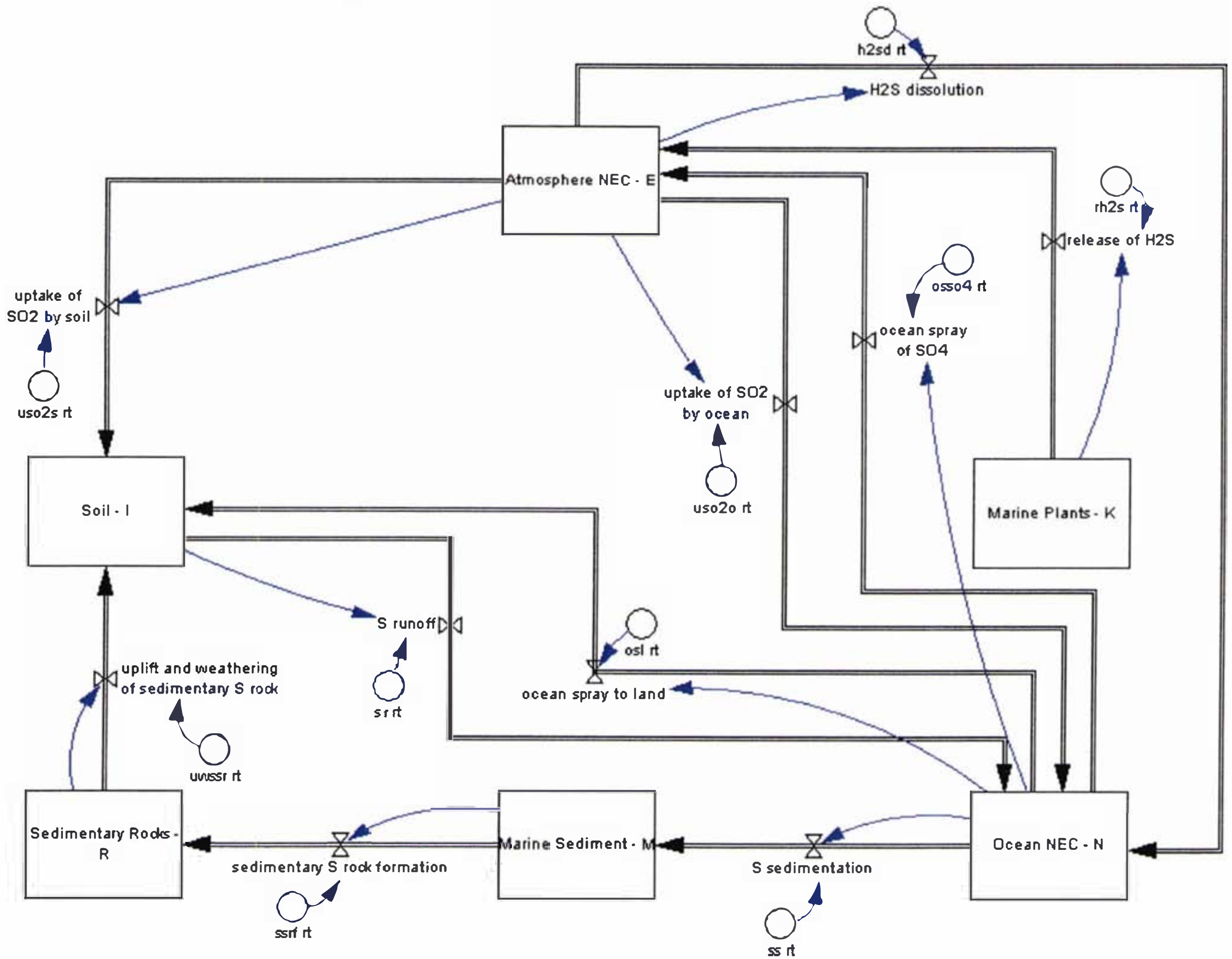


Figure B.4 **Sulphur Cycle Influence Diagram**

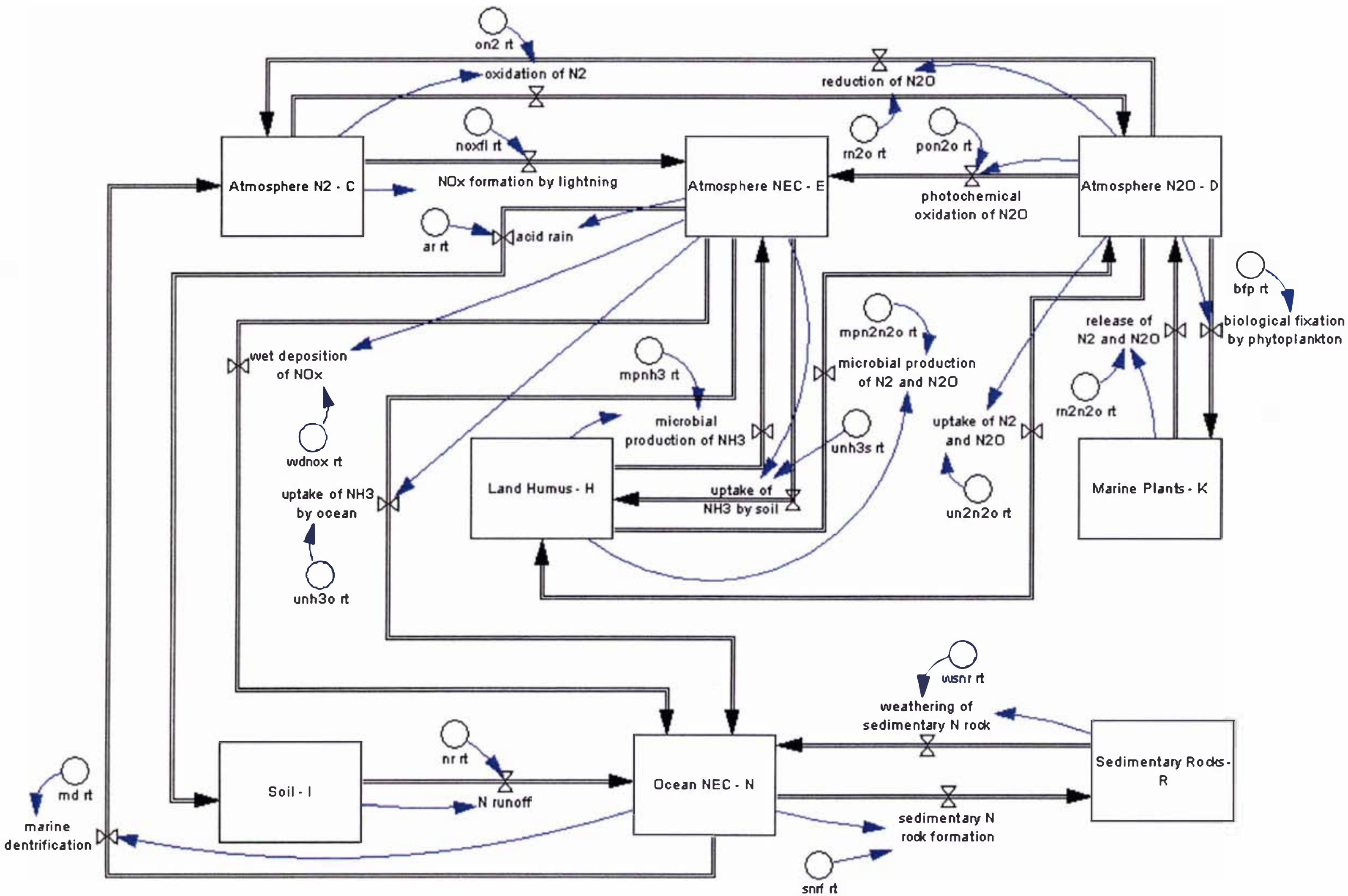


Figure B.5 Nitrogen Cycle Influence Diagram

B.5 Steady State Analysis

Once the model equations have been constructed the model may be run to established steady state conditions. Under ideal conditions the model should be at, or near, steady state prior to any investigation of the consequences of possible anthropogenic perturbations. Steady state conditions will only prevail in GBCM if the elemental masses of all inflows and outflows equate across each stock. Small differences may however result due to the complex feedbacks between stocks – particularly if reservoir masses or flux rates are incorrectly specified due to poor data quality. One approach commonly used in system dynamics modelling to overcome such discrepancies, is to run the model without perturbation over a long time frame (say 50 to 100 yrs) to (hopefully) establish its steady state conditions. Such an approach is only possible if (1) the model is near steady state equilibrium at its initialisation, and (2) any discrepancies represent only minor aberrations.

Figures B.6(a) to B.6(n) record the critical stock values of key reservoirs in the GBCM prior to any anthropogenic perturbation. These Figures reveal that the majority of critical stock values within the GBCM quickly moved toward their steady state values over a period of 50 years i.e. the GBCM's initial conditions produced results near the steady state equilibrium. On this basis, it was then possible to take the results at the end of the 50 year period and feed these back into the model as the initial conditions thus producing the steady state conditions at the model's initialisation. It should be noted that element stocks for the lithosphere are not included as these do not change over the specified 50 year time period.

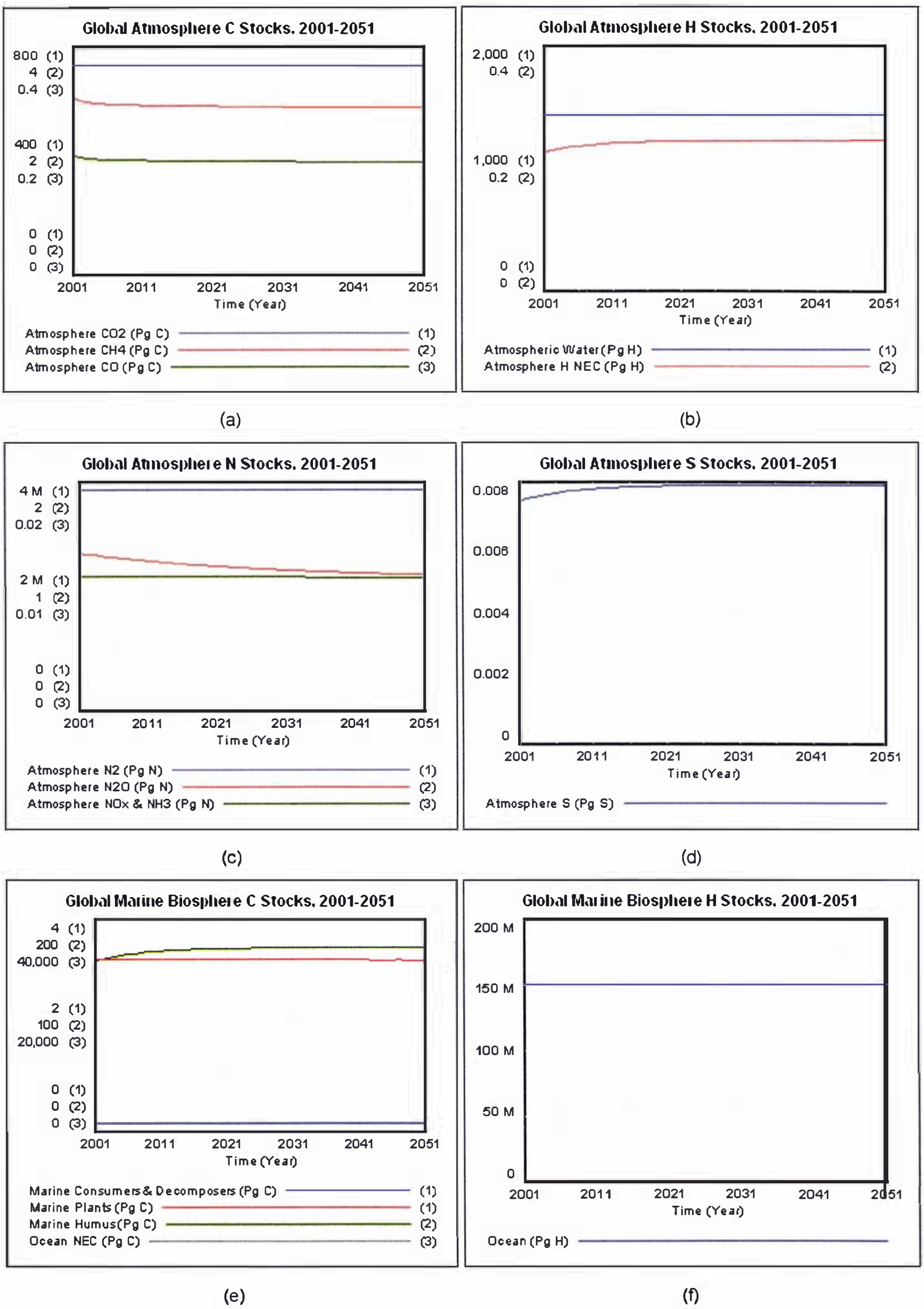
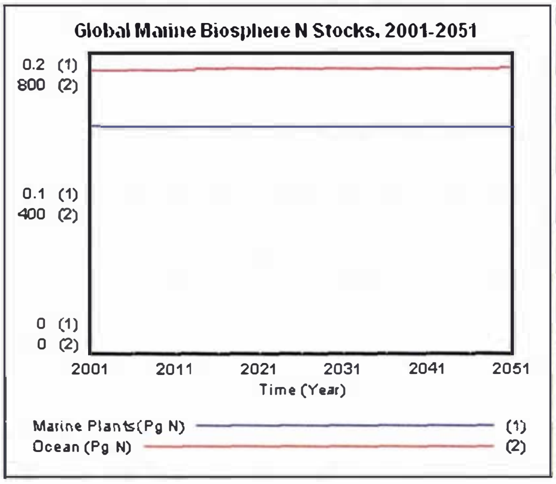
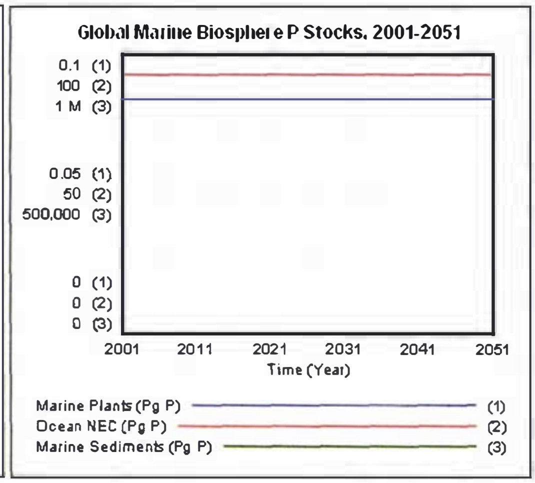
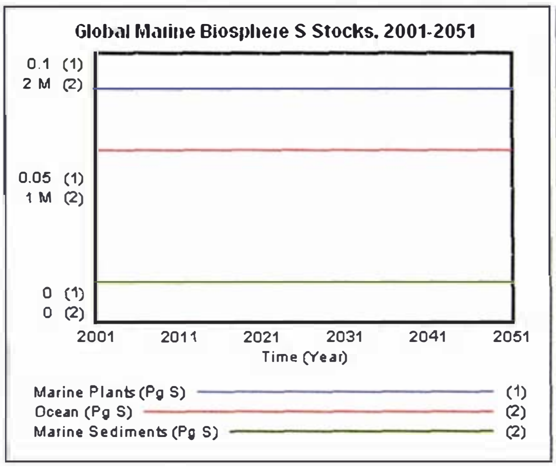


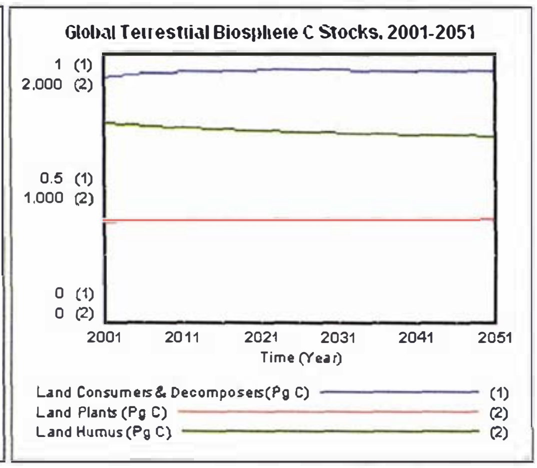
Figure B.6 **Baseline Analysis of the Steady State Conditions of Critical Atmosphere Stocks in the GBCM, 2001-2051**



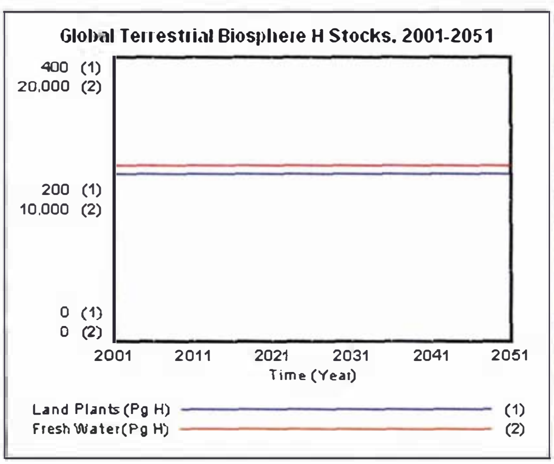


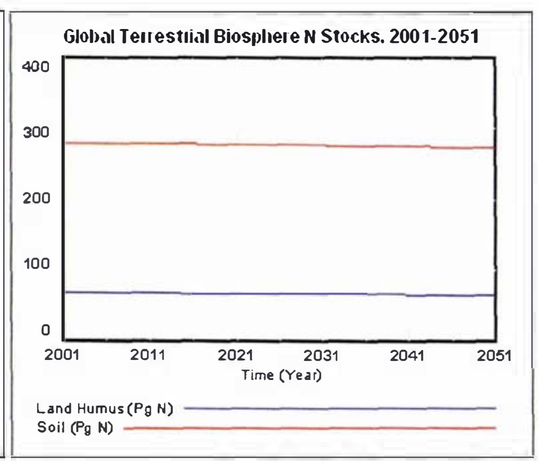
(g) (h)





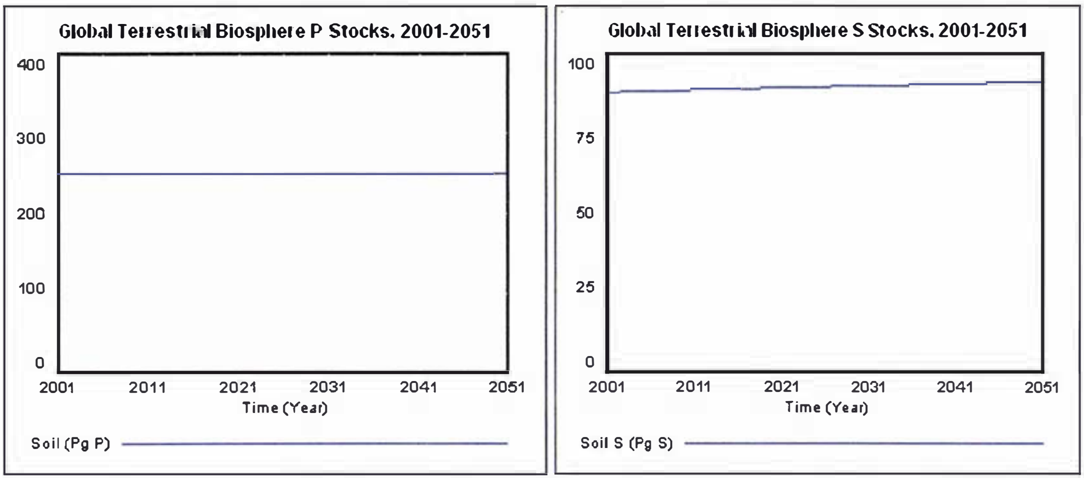
(i) (j)





(k) (l)

Figure B.6 **Baseline Analysis of the Steady State Conditions of Critical Atmosphere Stocks in the GBCM, 2001-2051 (Continued)**



(m) (n)

Figure B.6 **Baseline Analysis of the Steady State Conditions of Critical Atmosphere Stocks in the GBCM, 2001-2051 (Continued)**

B.6 Limitations and Caveats of the GBCM

There are several limitations and caveats of the GBCM including:

- *Scenario analysis through anthropogenic perturbation.* Scenarios need to be formulated to simulate these implications of human perturbation of the biogeochemical cycles. This could include: (1) depletion of a non-renewable natural resource stocks, (2) unsustainable harvests of renewable resource stocks (i.e. harvest plus natural decrease rates > regeneration rates), (3) exogenous injection of residuals into stocks, (4) one-off stochastic events, and (5) any combination of above.
- *Temporal dimension - stiff system.* The model is a stiff system i.e. the biogeochemical processes operate over diverse time frames, with residence times ranging from nanoseconds to geological time. The consequences of change on the slower parts of the cycle are therefore difficult to establish.
- *Spatial dynamics.* The effects of many of the ecological processes identified in the GCBM occur across distinct local areas. To capture these effects accurately a spatial dimension would need to be added to the GCBM. This would allow impacts to be assigned to, say, biomes or bioregions. It is however noted that spatial dynamic modelling is still very much in its infancy; refer to Costanza and Voinov (2004) for further details.

B.7 Finite Difference Equations for the GBCM

In this Section a full set of finite difference equations is presented for the GBCM. These equations adopt the conventions outlined above in Section B.4 of this Appendix. Table B.8 provides details of the arrayed flows, and sets of processes, used in describing the non-marker element flows in the GBCM.

Table B.8 Non-marker Arrayed Flows and Sets of Processes

Stock	Set/ Process Name	Set Elements/Processes
Atmosphere Stocks		
Atmosphere CO2	aco2rp	igneous rock formation, land humus formation (c&d), land humus formation (p), microbial production of N2 and N2O, microbial production of NH3, P particulate flux, production of CH4, release of H2S, release of N2 and N2O, oxidation of land humus, volcanic action, land plant respiration, tropospheric oxidation of CO, release of CO2
	aco2dp	biological fixation by phytoplankton, uptake of N2 and N2O, uptake of NH3 by soil, absorption of CO2 ,gross land production
Atmosphere CH4	ach4rp	microbial production of NH3, production of CH4, release of H2S
	ach4dp	oxidation of CH4, uptake of NH3 by soil
Atmosphere N2	an2rp	coal formation, igneous rock formation, kerogen formation, microbial production of N2 and N2O, release of N2 and N2O, volcanic action
	an2dp	biological fixation by phytoplankton, NOx formation by lightning, uptake of N2 and N2O
Atmosphere N2O	an2orp	microbial production of N2 and N2O, oxidation of N2, release of N2 and N2O
	an2odp	biological fixation by phytoplankton, photochemical oxidation of N2O, reduction of N2O, uptake of N2 and N2O
Atmosphere NEC	anecrp	oxidation of CH4, NOx formation by lightning, photochemical oxidation of N2O, H2S dissolution, coal formation, igneous rock formation, microbial production of NH3, oxidation of marine humus, production of CH4, release of H2S sub, volcanic action, production of CO, ocean spray of SO4, evaporation of soluable P, formation of atmospheric P dust particles
	anecdp	deposition of soluable P, uptake of NH3 by soil, tropospheric oxidation of CO, sorption of CO, wet deposition of NOx, acid rain, uptake of NH3 by ocean, uptake of SO2 by ocean, uptake of SO2 by soil, deposition of insoluable P, dissolution of atmospheric P dust particles
Terrestrial Biosphere Stocks		
Land Cons & Decomps	lcdrp	land consumption
	lcddp	land humus formation (c&d), production of CH4
Land Plants	lprp	gross land production, uptake of H2O
	lpdp	land consumption, land humus formation (p), land plant respiration, transpiration
Land Humus	lhrp	land humus formation (c&d), land humus formation (p), sorption of CO, uptake of N2 and N2O, uptake of NH3 by soil
	lhdp	coal formation, microbial production of N2 and N2O, microbial production of NH3, oxidation of land humus, transfer of land humus
Soil	srp	coal formation, dissolution of atmospheric P dust particles, land consumption, land humus formation (c&d), land humus formation (p), land plant respiration, microbial production of N2 and N2O, microbial production of NH3, oxidation of land humus, production of CH4, volcanic action, weathering of sedimentary P rock, acid rain, uptake of SO2 by soil, ocean spray to land, uplift and weathering of sedimentary S rock
	sdp	coal formation, formation of atmospheric P dust particles, gross land production, land consumption, land humus formation (p), P runoff, soil to ocean P sediments, sorption of CO, uptake of N2 and N2O, uptake of NH3 by soil, weathering of limestone, N runoff, S runoff
Marine Biosphere Stocks		
Marine Cons & Decomps	mcdrp	marine consumption
	mcddp	marine humus formation (c&d), production of CO
Marine Plants	mprp	biological fixation by phytoplankton, gross marine production, gross marine production
	mpdp	marine consumption, marine humus formation (p), marine plant respiration, P particulate flux, production of CaCO3, release of H2S, release of N2 and N2O
Marine Humus	mhrp	marine humus formation (c&d), marine humus formation (p), transfer of land humus
	mhdp	kerogen formation, oxidation of marine humus
Marine Sediments	msrp	deposition of insoluable P, P sedimentation, S sedimentation, soil to ocean P sediments
	msdp	sedimentary P rock formation, sedimentary S rock formation
Ocean NEC	onecrp	absorption of CO2, deposition of soluable P, H2S dissolution, marine humus formation (c&d), marine humus formation (p), marine plant respiration, oxidation of marine humus, P particulate flux, production of CaCO3, production of CO, release of H2S, release of N2 and N2O, transfer of land humus, weathering of limestone, wet deposition of NOx, uptake of NH3 by ocean, N runoff, weathering of sedimentary N rock, uptake of SO2 by ocean, S runoff, P runoff
	onecdp	S sedimentation, biological fixation by phytoplankton, evaporation of soluable P, gross marine production, igneous rock formation, kerogen formation, marine consumption, marine dentrification, P particulate flux, P sedimentation, release of CO2, sedimentary N rock formation, transfer of land humus, formation of limestone, ocean spray of SO4, ocean spray to land

Table B.8 Non-marker Arrayed Flows and Sets of Processes (Continued)

Stock	Set/ Process Name	Set Elements/Processes
Hydrosphere Stocks		
Atmosphere H2O	ah2orp	evaporation of soluable P, transpiration, evaporation from ocean, evaporation from land, photooxidation of H2, oxidation of CH4
	ah2odp	deposition of soluable P, H2S dissolution, precipitation to land, precipitation to ocean
Freshwater H2O	fh2orp	coal formation, land humus formation (c&d), land humus formation (p), land plant respiration, microbial production of N2 and N2O, oxidation of land humus, uptake of NH3 by soil, volcanic action, precipitation to land
	fh2odp	gross land production, microbial production of NH3, production of CH4, sorption of CO, uptake of N2 and N2O, evaporation from land, uptake of H2O, river discharge
Ocean H2O	oh2orp	marine dentrification, marine humus formation (c&d), marine humus formation (p), marine plant respiration, P particulate flux, P sedimentation, production of CaCO3, production of CO, release of CO2, release of N2 and N2O, transfer of land humus, precipitation to ocean, river discharge
	oh2odp	absorption of CO2, biological fixation by phytoplankton, gross marine production, kerogen formation, marine consumption, oxidation of marine humus, release of H2S, evaporation from ocean
Lithosphere Stocks		
Sedimentary Rocks	srrp	formation of limestone, sedimentary N rock formation, sedimentary P rock formation
	srdp	weathering of limestone, weathering of sedimentary N rock, weathering of sedimentary
Fossil Fuels	ffrp	coal formation, kerogen formation
	ffdp	igneous rock formation
Igneous Rocks	irrp	igneous rock formation
	irdp	volcanic action
Miscellaneous Stocks		
Oxygen	o2rp	biological fixation by phytoplankton, coal formation, gross land production, gross marine production, land consumption, marine consumption, ocean spray of SO4, production of CH4, sedimentary N rock formation, sedimentary S rock formation, sorption of CO, uptake of N2 and N2O, reduction of N2O
	o2dp	tropospheric oxidation of CO, acid rain, igneous rock formation, kerogen formation, land humus formation (c&d), land humus formation (p), land plant respiration, marine humus formation (c&d), marine humus formation (p), marine plant respiration, microbial production of N2 and N2O, oxidation of land humus, oxidation of marine humus, P particulate flux, photooxidation of H2, production of CaCO3, production of CO, release of N2 and N2O, transfer of land humus, uplift and weathering of sedimentary S rock, uptake of SO2 by ocean, uptake of SO2 by soil, volcanic action, weathering of sedimentary N rock, wet deposition of NOx, oxidation of CH4, oxidation of N2, NOx formation by lightning, photochemical oxidation of N2O

B.7.1 Atmosphere Stocks

$Atmosphere\ CO2_e(t + dt)$ $= Atmosphere\ CO2_e(t) + (atmos\ CO2\ from\ op_e + land\ plant\ respiration_e + oxidation\ of\ land\ humus_e + release\ of\ CO2_e + tropospheric\ oxidation\ of\ CO_e + volcanic\ action_e - absorption\ of\ CO2_e - atmos\ CO2\ for\ op_e - gross\ land\ production_e) \times dt$

where:

Initial $Atmosphere\ CO2_e$ $= initial\ atmos\ CO2_e$ for the 1998 base year

$atmos\ CO2\ from\ op_e$ $= \sum_{aco2rp=1}^{m} (atmos\ CO2\ nmrsm_{aco2rp,e} \times \sum_{e=1}^{n} (\{atmos\ CO2\ nmrsm\ processes_{aco2rp,e}\}))$

$absorption\ of\ CO2_e$ $= Atmosphere\ CO2_e(t) \times aco2\ rt_e$

atmos CO2 for op_e	$= \sum_{aco2dp=1}^{m} (atmos\ CO2\ nmdsm_{aco2dp,e} \times \sum_{e=1}^{n} (\{atmos\ CO2\ nmdsm\ processes_{aco2dp,e}\}))$
gross land $production_e$	$= Atmosphere\ CO2_e(t) \times glp\ rt_e$
Atmosphere $CH4_e(t + dt)$	$= Atmosphere\ CH4_e(t) + (atmos\ CH4\ from\ op_e + production\ of\ CH4_e - atmos\ CH4\ for\ op_e - oxidation\ of\ CH4_e) \times dt$
where:	
Initial *Atmosphere* $CH4_e$	$= initial\ atmos\ CH4_e$ for the 1998 base year
atmos CH4 from op_e	$= \sum_{ach4rp=1}^{m} (atmos\ CH4\ nmrsm_{ach4rp,e} \times \sum_{e=1}^{n} (\{atmos\ CH4\ nmrsm\ processes_{ach4rp,e}\}))$
atmos CH4 for op_e	$= \sum_{ach4dp=1}^{m} (atmos\ CH4\ nmdsm_{ach4dp,e} \times \sum_{e=1}^{n} (\{atmos\ CH4\ nmdsm\ processes_{ach4dp,e}\}))$
oxidation of $CH4_e$	$= Atmosphere\ CH4_e(t) \times och4\ rt_e$
Atmosphere $N2_e(t + dt)$	$= Atmosphere\ N2_e(t) + (atmos\ N2\ from\ op_e + marine\ dentrification_e + reduction\ of\ N2O_e - atmos\ N2\ for\ op_e - NOx\ formation\ by\ lightning_e - oxidation\ of\ N2_e) \times dt$
where:	
Initial *Atmosphere* $N2_e$	$= initial\ atmos\ N2_e$ for the 1998 base year
atmos N2 from op_e	$= \sum_{an2rp=1}^{m} (atmos\ N2\ nmrsm_{an2rp,e} \times \sum_{e=1}^{n} (\{atmos\ N2\ nmrsm\ processes_{an2rp,e}\}))$
atmos N2 for op_e	$= \sum_{an2dp=1}^{m} (atmos\ N2\ nmdsm_{an2dp,e} \times \sum_{e=1}^{n} (\{atmos\ N2\ nmdsm\ processes_{an2dp,e}\}))$
NOx formation by $lightning_e$	$= Atmosphere\ N2_e(t) \times noxfl\ rt_e$
oxidation of $N2_e$	$= Atmosphere\ N2_e(t) \times on2\ rt_e$
Atmosphere $N2O_e(t + dt)$	$= Atmosphere\ N2O_e(t) + (atmos\ N2O\ from\ op_e + microbial\ production\ of\ N2\ and\ N2O_e + oxidation\ of\ N2_e + release\ of\ N2\ and\ N2O_e - atmos\ N2O\ for\ op_e - biological\ fixation\ by\ phytoplankton_e - photochemical\ oxidation\ of\ N2O_e - reduction\ of\ N2O_e - uptake\ of\ N2\ and\ N2O_e) \times dt$

where:

Initial *Atmosphere* $N2O_e$ = *initial atmos* $N2O_e$ for the 1998 base year

atmos N2O from op_e = $\sum_{an2orp=1}^{m}(atmos\ N2O\ nmrsm_{an2orp,e} \times \sum_{e=1}^{n}(\{atmos\ N2O\ nmrsm\ processes_{an2orp,e}\}))$

atmos N2O for op_e = $\sum_{an2odp=1}^{m}(atmos\ N2O\ nmdsm_{an2odp,e} \times \sum_{e=1}^{n}(\{atmos\ N2O\ nmdsm\ processes_{an2odp,e}\}))$

biological fixation by $phytoplankton_e$ = *Atmosphere* $N2O_e(t) \times bfp\ rt_e$

photochemical oxidation of $N2O_e$ = *Atmosphere* $N2O_e(t) \times pon2o\ rt_e$

reduction of $N2O_e$ = *Atmosphere* $N2O_e(t) \times rn2o\ rt_e$

uptake of N2 and $N2O_e$ = *Atmosphere* $N2O_e(t) \times un2n2o\ rt_e$

Atmosphere $NEC_e(t + dt)$ = *Atmosphere* $NEC_e(t)$ + (*atmos nec from* op_e + *evaporation of soluable* P_e + *formation of atmospheric P dust* $particles_e$ + *microbial production of* $NH3_e$ + *NOx formation by* $lightning_e$ + *ocean spray of* $SO4_e$ + *oxidation of* $CH4_e$ + *photochemical oxidation of* $N2O_e$ + *production of* CO_e + *release of* $H2S_e$ - *uptake of SO2 by* $ocean_e$ - *uptake of SO2 by* $soil_e$ - *acid* $rain_e$ - *atmos nec for* op_e - *deposition of insoluable* P_e - *deposition of soluable* P_e - *dissolution of atmospheric P dust* $particles_e$ - *H2S* $dissolution_e$ - *photooxidation of* $H2_e$ - *sorption of* CO_e - *uptake of NH3 by* $ocean_e$ - *uptake of NH3 by* $soil_e$ - *wet deposition of* NOx_e - *tropospheric oxidation of* CO_e) × *dt*

where:

Initial *Atmosphere* NEC_e = *initial atmos* nec_e for the 1998 base year

atmos nec from op_e = $\sum_{anecrp=1}^{m}(atmos\ nec\ nmrsm_{anecrp,e} \times \sum_{e=1}^{n}(\{atmos\ nec\ nmrsm\ processes_{anecrp,e}\}))$

acid $rain_e$ = *Atmosphere* $NEC_e(t) \times ar\ rt_e$

atmos nec for op_e = $\sum_{anecdp=1}^{m}(atmos\ nec\ nmdsm_{anecdp,e} \times \sum_{e=1}^{n}(\{atmos\ nec\ nmdsm\ processes_{anecdp,e}\}))$

deposition of insoluable P_e = *Atmosphere* $NEC_e(t) \times dip\ rt_e$

deposition of soluable P_e = *Atmosphere* $NEC_e(t) \times dsp\ rt_e$

dissolution of atmospheric P dust $particles_e$ = *Atmosphere* $NEC_e(t) \times dapdp\ rt_e$

H2S dissolution$_e$	= *Atmosphere NEC*$_e(t)$ × *h2sd rt*$_e$
photooxidation of H2$_e$	= *Atmosphere NEC*$_e(t)$ × *ph2 rt*$_e$
sorption of CO$_e$	= *Atmosphere NEC*$_e(t)$ × *sco rt*$_e$
tropospheric oxidation of CO$_e$	= *Atmosphere NEC*$_e(t)$ × *toco rt*$_e$
uptake of NH3 by ocean$_e$	= *Atmosphere NEC*$_e(t)$ × *unh3o rt*$_e$
uptake of NH3 by soil$_e$	= *Atmosphere NEC*$_e(t)$ × *unh3s rt*$_e$
uptake of SO2 by ocean$_e$	= *Atmosphere NEC*$_e(t)$ × *uso2o rt*$_e$
uptake of SO2 by soil$_e$	= *Atmosphere NEC*$_e(t)$ × *uso2s rt*$_e$
wet deposition of NOx$_e$	= *Atmosphere NEC*$_e(t)$ × *wdnox rt*$_e$

B.7.2 Terrestrial Stocks

Land Consumers and Decomposers$_e(t + dt)$ = *Land Consumers and Decomposers*$_e(t)$ + (*land cons & decomps from op*$_e$ + *land consumption*$_e$ - *land cons & decomps for op*$_e$ - *land humus formation (c&d)*$_e$ - *production of CH4*$_e$) × *dt*

where:

Initial *Land Consumers and Decomposers*$_e$ = *initial land cons & decomps*$_e$ for the 1998 base year

land cons & decomps from op$_e$ = $\sum_{lcdrp=1}^{m}$ (*land cons & decomps nmrsm*$_{lcdrp,e}$ × $\sum_{e=1}^{n}$({*land cons & decomps nmdsm processes*$_{lcdrp,e}$}))

land cons & decomps for op$_e$ = $\sum_{lcddp=1}^{m}$ (*land cons & decomps nmdsm*$_{lcddp,e}$ × $\sum_{e=1}^{n}$({*land cons & decomps nmdsm processes*$_{lcddp,e}$}))

land humus formation (c&d)$_e$ = *Land Consumers and Decomposers*$_e(t)$ × *lhfcd rt*$_e$

production of CH4$_e$ = *Land Consumers and Decomposers*$_e(t)$ × *pch4 rt*$_e$

Land Plants$_e(t + dt)$ = *Land Plants*$_e(t)$ + (*gross land production*$_e$ + *land plants from op*$_e$ + *uptake of H2O*$_e$ - *land consumption*$_e$ - *land humus formation (p)*$_e$ - *land plant respiration*$_e$ - *land plants for op*$_e$ - *transpiration*$_e$) × *dt*

where:

Initial *Land Plants*$_e$ = *initial land plants*$_e$ for the 1998 base year *land plants from* op_e $= \sum_{lprp=1}^{m} (\text{land plants nmrsm}_{lprp,e} \times \sum_{e=1}^{n} (\{\text{land plants nmrsm processes}_{lprp,e}\}))$

land consumption$_e$ $= \text{Land Plant}_e(t) \times lc\ rt_e$

land humus formation (p)$_e$ $= \text{Land Plant}_e(t) \times lhfp\ rt_e$

land plants for op_e $= \sum_{lpdp=1}^{m} (\text{land plants nmdsm}_{lpdp,e} \times \sum_{e=1}^{n} (\{\text{land plants nmdsm processes}_{lpdp,e}\}))$

land plant respiration$_e$ $= \text{Land Plant}_e(t) \times lpr\ rt_e$

transpiration$_e$ $= \text{Land Plant}_e(t) \times t\ rt_e$

Land Humus$_e(t + dt)$ = *Land Humus*$_e(t)$ + (*land humus formation (c&d)*$_e$ + *land humus formation (p)*$_e$ + *land humus from* op_e + *sorption of* CO_e + *uptake of N2 and N2O*$_e$ + *uptake of NH3 by soil*$_e$ - *coal formation*$_e$ - *land humus for* op_e - *microbial production of N2 and N2O*$_e$ - *microbial production of NH3*$_e$ - *oxidation of land humus*$_e$ - *transfer of land humus*$_e$) × *dt*

where:

Initial *Land Humus*$_e$ = *initial land humus*$_e$ for the 1998 base year

land humus from op_e $= \sum_{lhrp=1}^{m} (\text{land humus nmrsm}_{lhrp,e} \times \sum_{e=1}^{n} (\{\text{land humus nmrsm processes}_{lhrp,e}\}))$

coal formation$_e$ $= \text{Land Humus}_e(t) \times cf\ rt_e$

land humus for op_e $= \sum_{lhdp=1}^{m} (\text{land humus nmdsm}_{lhdp,e} \times \sum_{e=1}^{n} (\{\text{land humus nmdsm processes}_{lhdp,e}\}))$

microbial production of N2 and N2O$_e$ $= \text{Land Humus}_e(t) \times mpn2n2o\ rt_e$

microbial production of NH3$_e$ $= \text{Land Humus}_e(t) \times mpnh3\ rt_e$

oxidation of land humus$_e$ $= \text{Land Humus}_e(t) \times olh\ rt_e$

transfer of land humus$_e$ $= \text{Land Humus}_e(t) \times tlh\ rt_e$

Soil$_e(t + dt)$ = *Soil*$_e(t)$ + (*acid rain*$_e$ + *dissolution of atmospheric P dust particles*$_e$ + *ocean spray to land*$_e$ + *soil from* op_e + *uplift and weathering of sedimentary S rock*$_e$ + *uptake of SO2 by soil*$_e$ + *weathering of sedimentary P rock*$_e$ - *formation of atmospheric*

$P\ dust\ particles_e$ - $N\ runoff_e$ - $P\ runoff_e$ - $S\ runoff_e$ - $soil\ for\ op_e$ - $soil\ to\ ocean\ P\ sediments_e) \times dt$

where:

Initial $Soil_e$ = $initial\ soil_e$ for the 1998 base year

$soil\ from\ op_e$ $= \sum_{srp=1}^{m} (soil\ nmrsm_{srp,e} \times \sum_{e=1}^{n} (\{soil\ nmrsm\ processes_{srp,e}\}))$

$formation\ of\ atmospheric\ P\ dust\ particles_e = Soil_e(t) \times fapdp\ rt_e$

$N\ runoff_e$ $= Soil_e(t) \times nr\ rt_e$

$P\ runoff_e$ $= Soil_e(t) \times pr\ rt_e$

$S\ runoff_e$ $= Soil_e(t) \times sr\ rt_e$

$soil\ for\ op_e$ $= \sum_{sdp=1}^{m} (soil\ nmdsm_{sdp,e} \times \sum_{e=1}^{n} (\{soil\ nmdsm\ processes_{sdp,e}\}))$

$soil\ to\ ocean\ P\ sediments_e$ $= Soil_e(t) \times sops\ rt_e$

B.7.3 Marine Stocks

$Marine\ Consumers\ and\ Decomposers_e(t + dt) = Marine\ Consumers\ and\ Decomposers_e(t) + (marine\ cons\ \&\ decomps\ from\ op_e + marine\ consumption_e$ - $marine\ cons\ \&\ decomps\ for\ op_e$ - $marine\ humus\ formation\ (c\&d)_e$ - $production\ of\ CO_e) \times dt$

where:

Initial $Marine\ Consumers\ and\ Decomposers_e$ = $initial\ marine\ cons\ \&\ decomps_e$ for the 1998 base year

$marine\ cons\ \&\ decomps\ from\ op_e = \sum_{mcdrp=1}^{m} (marine\ cons\ \&\ decomps\ nmrsm_{mcdrp,e} \times \sum_{e=1}^{n} (\{marine\ cons\ \&\ decomps\ nmrsm\ processes_{mcdrp,e}\}))$

$marine\ cons\ \&\ decomps\ for\ op_e = \sum_{mcddp=1}^{m} (marine\ cons\ \&\ decomps\ nmdsm_{mcddp,e} \times \sum_{e=1}^{n} (\{marine\ cons\ \&\ decomps\ nmdsm\ processes_{mcddp,e}\}))$

$marine\ humus\ formation\ (c\&d)_e = Marine\ Consumers\ and\ Decomposers_e(t) \times mhfcd\ rt_e$

$production\ of\ CO_e$ $= Marine\ Consumers\ and\ Decomposers_e(t) \times pco\ rt_e$

$Marine\ Plants_e(t + dt)$ $= Marine\ Plants_e(t) + (biological\ fixation\ by\ phytoplankton_e + gross\ marine\ production_e + marine\ plants\ from\ op_e$ - $marine\ consumption_e$ - $marine\ humus\ formation\ (p)_e$ - $marine\ plant$

respiration$_e$ - *marine plants for op*$_e$ - *P particulate flux*$_e$ - *production of CaCO3*$_e$ - *release of H2S*$_e$ - *release of N2 and N2O*$_e$) × *dt*

where:

Initial *Marine Plants*$_e$ = *initial marine plants*$_e$ for the 1998 base year

marine plants from op$_e$ $= \sum_{mprp=1}^{m} (\textit{marine plants nmrsm}_{mprp,e} \times \sum_{e=1}^{n} (\{\textit{marine plants nmrsm processes}_{mprp,e}\}))$

marine consumption$_e$ = *Marine Plants*$_e$(*t*) × *mc rt*$_e$

marine humus formation (p)$_e$ = *Marine Plants*$_e$(*t*) × *mhfp rt*$_e$

marine plant respiration$_e$ = *Marine Plants*$_e$(*t*) × *mpr rt*$_e$

marine plants for op$_e$ $= \sum_{mpdp=1}^{m} (\textit{marine plants nmdsm}_{mpdp,e} \times \sum_{e=1}^{n} (\{\textit{marine plants nmdsm processes}_{mpdp,e}\}))$

P particulate flux$_e$ = *Marine Plants*$_e$(*t*) × *ppf rt*$_e$

production of CaCO3$_e$ = *Marine Plants*$_e$(*t*) × *pcaco3 rt*$_e$

release of H2S$_e$ = *Marine Plants*$_e$(*t*) × *rh2s rt*$_e$

release of N2 and N2O$_e$ = *Marine Plants*$_e$(*t*) × *rn2n2o rt*$_e$

Marine Humus$_e$(*t* + *dt*) = *Marine Humus*$_e$(*t*) + (*marine humus formation (c&d)*$_e$ + *marine humus formation (p)*$_e$ + *marine humus from op*$_e$ + *transfer of land humus*$_e$ - *kerogen formation*$_e$ - *marine humus for op*$_e$ - *oxidation of marine humus*$_e$) × *dt*

where:

Initial *Marine Humus*$_e$ = *initial marine humus*$_e$ for the 1998 base year

marine humus from op$_e$ $= \sum_{mhrp=1}^{m} (\textit{marine humus nmrsm}_{mhrp,e} \times \sum_{e=1}^{n} (\{\textit{marine humus nmrsm processes}_{mhrp,e}\}))$

kerogen formation$_e$ = *Marine Humus*$_e$(*t*) × *kf rt*$_e$

marine humus for op$_e$ $= \sum_{mhdp=1}^{m} (\textit{marine humus nmdsm}_{mhdp,e} \times \sum_{e=1}^{n} (\{\textit{marine humus nmdsm processes}_{mhdp,e}\}))$

oxidation of marine humus$_e$ = *Marine Humus*$_e$(*t*) × *omh rt*$_e$

Marine Sediment$_e$(*t* + *dt*) = *Marine Sediment*$_e$(*t*) + (*deposition of insoluable P*$_e$ + *marine sediments from op*$_e$ + *P sedimentation*$_e$ + *S sedimentation*$_e$ +

soil to ocean P sediments$_e$ *- sedimentary P rock formation*$_e$ *- marine sediments for op*$_e$ *- sedimentary S rock formation*$_e$*)* × *dt*

where:

Initial *Marine Sediment*$_e$ = *initial marine sediment*$_e$ for the 1998 base year

marine sediments from op$_e$ $= \sum_{msrp=1}^{m} (\mathit{marine\ sediments\ nmrsm}_{msrp,e} \times \sum_{e=1}^{n} (\{\mathit{marine\ sediments\ nmrsm\ processes}_{msrp,e}\}))$

marine sediments for op$_e$ $= \sum_{msdp=1}^{m} (\mathit{marine\ sediments\ nmdsm}_{msdp,e} \times \sum_{e=1}^{n} (\{\mathit{marine\ sediments\ nmdsm\ processes}_{msdp,e}\}))$

sedimentary P rock formation$_e$ = *Marine Sediment*$_e$*(t)* × *sprf rt*$_e$

sedimentary S rock formation$_e$ = *Marine Sediment*$_e$*(t)* × *ssrf rt*$_e$

Ocean NEC$_e$*(t + dt)* = *Ocean NEC*$_e$*(t)* + (*absorption of CO2*$_e$ + *deposition of soluable P*$_e$ + *H2S dissolution*$_e$ + *marine plant respiration*$_e$ + *N runoff*$_e$ + *ocean nec from op*$_e$ + *oxidation of marine humus*$_e$ + *P particulate flux*$_e$ + *P runoff*$_e$ + *production of CaCO3*$_e$ + *S runoff*$_e$ + *uptake of NH3 by ocean*$_e$ + *uptake of SO2 by ocean*$_e$ + *weathering of limestone*$_e$ + *weathering of sedimentary N rock*$_e$ + *wet deposition of NOx*$_e$ *- ocean spray of SO4*$_e$ *- evaporation of soluable P*$_e$ *- formation of limestone*$_e$ *- gross marine production*$_e$ *- marine dentrification*$_e$ *- ocean nec for op*$_e$ *- ocean spray to land*$_e$ *- P sedimentation*$_e$ *- release of CO2*$_e$ *- S sedimentation*$_e$ *- sedimentary N rock formation*$_e$*)* × *dt*

where:

Initial *Ocean NEC*$_e$ = *initial ocean nec*$_e$ for the 1998 base year

ocean nec from op$_e$ $= \sum_{onecrp=1}^{m} (\mathit{ocean\ nec\ nmrsm}_{onecrp,e} \times \sum_{e=1}^{n} (\{\mathit{ocean\ nec\ nmrsm\ processes}_{onecrp,e}\}))$

evaporation of soluable P$_e$ = *Ocean NEC*$_e$*(t)* × *esp rt*$_e$

formation of limestone$_e$ = *Ocean NEC*$_e$*(t)* × *fl rt*$_e$

gross marine production$_e$ = *Ocean NEC*$_e$*(t)* × *gmp rt*$_e$

marine dentrification$_e$ = *Ocean NEC*$_e$*(t)* × *md rt*$_e$

ocean nec for op$_e$ $= \sum_{onecdp=1}^{m} (\mathit{ocean\ nec\ nmdsm}_{onecdp,e} \times \sum_{e=1}^{n} (\{\mathit{ocean\ nec\ nmdsm\ processes}_{onecdp,e}\}))$

ocean spray of $SO4_e$	$= Ocean\ NEC_e(t) \times osso4\ rt_e$
ocean spray to $land_e$	$= Ocean\ NEC_e(t) \times osl\ rt_e$
P $sedimentation_e$	$= Ocean\ NEC_e(t) \times ps\ rt_e$
release of $CO2_e$	$= Ocean\ NEC_e(t) \times rco2\ rt_e$
S $sedimentation_e$	$= Ocean\ NEC_e(t) \times ss\ rt_e$
sedimentary N rock $formation_e$	$= Ocean\ NEC_e(t) \times snrf\ rt_e$

B.7.4 Hydrosphere Stocks

$Atmosphere\ H2O_e(t + dt)$ $= Atmosphere\ H2O_e(t) + (atmos\ H2O\ from\ op_e + evaporation\ from\ land_e + evaporation\ from\ ocean_e + photooxidation\ of\ H2_e + transpiration_e - atmos\ H2O\ for\ op_e - precipitation\ to\ land_e - precipitation\ to\ ocean_e) \times dt$

where:

Initial $Atmosphere\ H2O_e$ $= initial\ atmos\ H2O_e$ for the 1998 base year

$atmos\ H2O\ from\ op_e$ $= \sum_{ah2orp=1}^{m} (atmos\ H2O\ nmrsm_{ah2orp,e} \times \sum_{e=1}^{n}(\{atmos\ H2O\ nmrsm\ processes_{ah2orp,e}\}))$

$atmos\ H2O\ for\ op_e$ $= \sum_{ah2odp=1}^{m} (atmos\ H2O\ nmdsm_{ah2odp,e} \times \sum_{e=1}^{n}(\{atmos\ H2O\ nmdsm\ processes_{ah2odp,e}\}))$

$precipitation\ to\ land_e$ $= Atmosphere\ H2O_e(t) \times pl\ rt_e$

$precipitation\ to\ ocean_e$ $= Atmosphere\ H2O_e(t) \times po\ rt_e$

$Freshwater\ H2O_e(t + dt)$ $= Freshwater\ H2O_e(t) + (freshwater\ H2O\ from\ op_e + precipitation\ to\ land_e - evaporation\ from\ land_e - freshwater\ H2O\ for\ op_e - river\ discharge_e - uptake\ of\ H2O_e) \times dt$

where:

Initial $Freshwater\ H2O_e$ $= initial\ freshwater\ H2O_e$ for the 1998 base year

$freshwater\ H2O\ from\ op_e$ $= \sum_{fh2orp=1}^{m} (freshwater\ H2O\ nmrsm_{fh2orp,e} \times \sum_{e=1}^{n}(\{freshwater\ H2O\ nmrsm\ processes_{fh2orp,e}\}))$

$evaporation\ from\ land_e$ $= Freshwater\ H2O_e(t) \times el\ rt_e$

$freshwater\ H2O\ for\ op_e$ $= \sum_{fh2odp=1}^{m} (freshwater\ H2O\ nmdsm_{fh2odp,e} \times \sum_{e=1}^{n}(\{freshwater\ H2O\ nmdsm\ processes_{fh2odp,e}\}))$

river discharge$_e$ = *Freshwater* $H2O_e(t) \times rd\ rt_e$

uptake of $H2O_e$ = *Freshwater* $H2O_e(t) \times uh2o\ rt_e$

Ocean $H2O_e(t + dt)$ = *Ocean* $H2O_e(t)$ + (*ocean H2O from* op_e + *precipitation to* $ocean_e$ + *river* $discharge_e$ - *evaporation from* $ocean_e$ - *ocean H2O for* op_e) $\times dt$

where:

Initial *Ocean* $H2O_e$ = *initial ocean* $H2O_e$ for the 1998 base year

ocean H2O from op_e $= \sum_{oh2orp=1}^{m} (ocean\ H2O\ nmrsm_{oh2orp,e} \times \sum_{e=1}^{n} (\{ocean\ H2O\ nmrsm\ processes_{oh2orp,e}\}))$

evaporation from $ocean_e$ = *Ocean* $H2O_e(t) \times eo\ rt_e$

ocean H2O for op_e $= \sum_{oh2odp=1}^{m} (ocean\ H2O\ nmdsm_{oh2odp,e} \times \sum_{e=1}^{n} (\{ocean\ H2O\ nmdsm\ processes_{oh2odp,e}\}))$

B.7.5 Lithosphere Stocks

Sedimentary $Rocks_e(t + dt)$ = *Sedimentary* $Rocks_e(t)$ + (*formation of* $limestone_e$ + *sedimentary N rock* $formation_e$ + *sedimentary P rock* $formation_e$ + *sedimentary rocks from* op_e + *sedimentary S rock* $formation_e$ - *sedimentary rocks for* op_e - *uplift and weathering of sedimentary S* $rock_e$ - *weathering of* $limestone_e$ - *weathering of sedimentary N* $rock_e$ - *weathering of sedimentary P* $rock_e$) $\times$ *dt*

where:

Initial *Sedimentary* $Rocks_e$ = *initial sedimentary* $rocks_e$ for the 1998 base year

sedimentary rocks from op_e $= \sum_{srrp=1}^{m} (sedimentary\ rocks\ nmrsm_{srrp,e} \times \sum_{e=1}^{n} (\{sedimentary\ rocks\ nmrsm\ processes_{srrp,e}\}))$

sedimentary rocks for op_e $= \sum_{srdp=1}^{m} (sedimentary\ rocks\ nmdsm_{srdp,e} \times \sum_{e=1}^{n} (\{sedimentary\ rocks\ nmdsm\ processes_{srdp,e}\}))$

uplift and weathering of sedimentary S $rock_e$ = *Sedimentary* $Rocks_e(t) \times uwssr\ rt_e$

weathering of $limestone_e$ = *Sedimentary* $Rocks_e(t) \times wl\ rt_e$

weathering of sedimentary N $rock_e$ = *Sedimentary* $Rocks_e(t) \times wsnr\ rt_e$

$weathering\ of\ sedimentary\ P\ rock_e = Sedimentary\ Rocks_e(t) \times wspr\ rt_e$

$Fossil\ Fuels_e(t + dt)$ $= Fossil\ Fuels_e(t) + (coal\ formation_e + fossil\ fuels\ from\ op_e + kerogen\ formation_e - fossil\ fuels\ for\ op_e - igneous\ rock\ formation_e) \times dt$

where:

Initial $Fossil\ Fuels_e$ $= initial\ fossil\ fuels_e$ for the 1998 base year

$fossil\ fuels\ from\ op_e$ $= \sum_{ffrp=1}^{m} (fossil\ fuels\ nmrsm_{ffrp,e} \times \sum_{e=1}^{n}(\{fossil\ fuels\ nmrsm\ processes_{ffrp,e}\}))$

$fossil\ fuels\ for\ op_e$ $= \sum_{ffdp=1}^{m} (fossil\ fuels\ nmdsm_{ffddp,e} \times \sum_{e=1}^{n}(\{fossil\ fuels\ nmdsm\ processes_{ffdp,e}\}))$

$igneous\ rock\ formation_e$ $= Fossil\ Fuels_e(t) \times irf\ rt_e$

$Igneous\ Rock_e(t + dt)$ $= Igneous\ Rock_e(t) + (igneous\ rock\ formation_e + igneous\ rocks\ from\ op_e - igneous\ rocks\ for\ op_e - volcanic\ action_e) \times dt$

where:

Initial $Igneous\ Rock_e$ $= initial\ igneous\ rock_e$ for the 1998 base year

$igneous\ rocks\ from\ op_e$ $= \sum_{irrp=1}^{m} (igneous\ rocks\ nmrsm_{irrp,e} \times \sum_{e=1}^{n}(\{igneous\ rocks\ nmrsm\ processes_{irrp,e}\}))$

$igneous\ rocks\ for\ op_e$ $= \sum_{irdp=1}^{m} (igneous\ rocks\ nmdsm_{irdp,e} \times \sum_{e=1}^{n}(\{igneous\ rocks\ nmdsm\ processes_{irdp,e}\}))$

$volcanic\ action_e$ $= Igneous\ Rock_e(t) \times va\ rt_e$

B.7.6 Oxygen Stock

$Oxygen_e(t + dt)$ $= Oxygen_e(t) + (O2\ from\ op_e - O2\ for\ op_e) \times dt$

where:

Initial $Oxygen_e$ $= initial\ O2_e$ for the 1998 base year

$O2\ from\ op_e$ $= \sum_{o2rp=1}^{m} (O2\ nmrsm_{o2rp,e} \times \sum_{e=1}^{n}(\{O2\ nmrsm\ processes_{o2rp,e}\}))$

$O2\ for\ op_e$ $= \sum_{o2dp=1}^{m} (O2\ nmdsm_{o2dp,e} \times \sum_{e=1}^{n}(\{O2\ nmdsm\ processes_{o2dp,e}\}))$

Appendix C

Mathematical Description of the Interregional Trade Flows Optimisation used in the Ecological Footprint Analysis

This Appendix describes the optimisation approach used to determine the interregional trade flows between the study region and its trading partners. The optimisation problem is portrayed diagrammatically in Figure C.1 and described mathematically below.

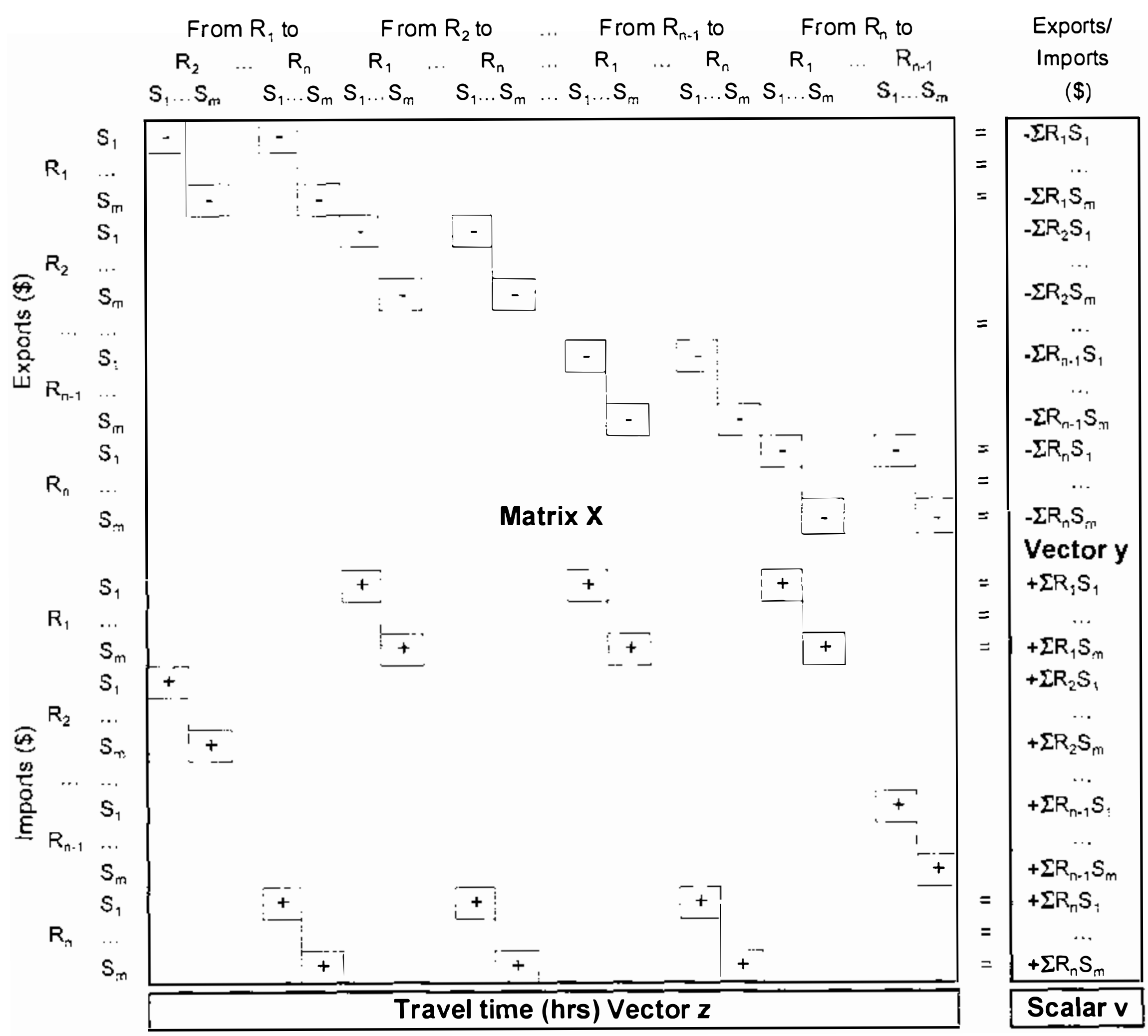


Figure C.1 Structure of the Interregional Trade Flows Optimisation Problem

The capital letters **R** and **S** are used respectively to denote regions and industries i.e., $\mathbf{R_1S_1}$ denotes Industry 1 in Region 1. The letter n represents the number of regions, while the letter m represents the number of industries.

Matrix **X** [n x m x 2, (n x $n - n$) x m]. This matrix describes the flow of trade between regions. A negative sign (-) denotes exports, while a positive sign (+) denotes imports. Column 1, for example, describes the trade flows between Region 1, $\mathbf{R}_1$, and Region 2, $\mathbf{R}_2$.

Vector y [n x m x 2, 1]. This column vector describes imports to, and exports from, each region by industry. The element in row 1, for example, represents the sum of all Industry 1 exports originating from Region 1, $-\sum \mathbf{R}_1\mathbf{S}_1$. The elements in this vector are used as binding constraints in the optimisation.

Vector z [1, (n x $n - n$) x m]. This row vector denotes freight haulage times between regions per dollar of trade flow. Freight haulage times are calculated using an origin-destination matrix.

Scalar v (1, 1). This scalar is the sum of row vector z. It represents the total freight travel time needed to move goods and services between all permutations of regions and industries. Minimisation of this scalar is the objective function.

The optimisation is solved as follows:

Min: $z\,w = v$

subject to:

$\mathbf{X}\,w = y$

$w >= 0$

where: w = column vector [(n x $n - n$) x m, 1] describing the flow ($) of m industry commodities between n regions to be solved for.

In the analysis undertaken in Chapter 8 of this thesis, there are 5,520 possible flows between industries that are quantitatively determined by solving for w.

Appendix D

Non-Survey Regionalisation Methodologies

This Appendix provides a brief outline of the most commonly used non-survey regionalisation methodologies. The intention is to provide only background knowledge rather than a comprehensive evaluation of non-survey methodologies[290]. For further information refer to Richardson (1972), Smith and Morrison (1974), Jensen *et al.* (1979), Sawyer and Miller (1983), Butcher (1985), Stevens *et al.* (1989), and Dietzenbacher and Lahr (2001).

The development of regional input-output methodologies began with Hirsch (1959), and produced studies of the economies of *inter alia* Boulder (Miernyk *et al.* 1967), West Virginia (Miernyk *et al.* 1970), Philadelphia (Isard and Langford, 1969; Isard, Langford, and Romanoff 1966-68; Isard and Langford, 1971), Kansas (Emerson and Hackman, 1971), and Washington (Bourque *et al.* 1967). These survey based studies were the product of coordinated research groups. They established best practice procedures that have subsequently been adopted by many countries in producing survey tables.

By the mid 1970s high costs and time delays associated with building survey based tables had led input-output analysts to seek alternative construction methods. The resulting non-survey approaches typically attempted to reduce national technical coefficients to the regional equivalents by purely mathematical means. Analysts such as Schaffer and Chu (1969), Smith and Morrison (1974), Eskelinen and Suosra (1980) and Sawyer and Miller (1983) conducted notable reviews of the leading non-survey methodologies. Their findings concluded that in general non-survey based approaches tend to overestimate inter-industry flows and underestimate exports, and by implication, overestimate multipliers. Although most analysts acknowledge that non-survey methods cannot be expected to represent adequately the complex interrelationships in a regional economy, as captured by a survey based approach, virtual consensus has emerged that supplementing non-survey based tables with superior survey data greatly improves the analytical accuracy of the regional table derived. The major non-survey techniques are discussed below.

[290] It should be noted that the techniques reviewed have for the most part only been assessed in the context of regionalising inter-industry matrices, rather than commodity-by-industry matrices as are used in this thesis.

D.1 Coefficient Reduction Methodologies

The location quotient, commodity balance and constrained matrix methodologies attempt to mechanically reduce national input-output coefficients to the regional level. The first two approaches operate on the premise that regional and national coefficients differ only be the magnitude of the regional import coefficient. The implicit assumption of maximum regional self-sufficiency means that these approaches will generally overestimate regional input-output coefficients. By comparison, the constrained matrix approach ruthlessly employs mathematical iteration to scale down national level intermediate demand transactions until input-output sub-totals approximate regional estimates.

D.1.1 Location Quotient Methodologies

The Simple Location Quotient Method

Schaffer and Chu (1969) assessed the performance of five non-survey techniques in estimating a regional input-output table for the 1958 State of Washington economy. The performance of each technique was assessed in terms of how the table generated compared with a survey based table for the same year. They found that the simple location quotient (SLQ) technique generally provided the best estimates of regional inter-industry structure. Similar studies conducted by Smith and Morrison (1974), Eskelinen and Suorsa (1980) and Sawyer and Miller (1983) all corroborated Schaffer and Chu's (1969) findings, namely that the SLQ technique produced the best estimates of the techniques reviewed, although coefficients were likely to be overestimated.

The SLQ method is arguably the most widely employed data reduction method. Smith and Morrison (1974) attribute this to its simplicity, modest data demands, and time and cost effectiveness. Essentially, this method compares the relative importance of regional industries, usually in terms of output or employment, to their relative importance nationally. Mathematically, the SLQ for industry j is calculated as follows:

$$slq_j = \left(\frac{\left(\frac{\beta_j^r}{\beta^r} \right)}{\left(\frac{\beta_j}{\beta} \right)} \right) \qquad \text{(D.1)}$$

where **β** represents output or employment and the superscript *r* the region. The regional input-output coefficients for each industry *j* may be determined by multiplying the national input-output coefficients for that industry *j* by the corresponding SLQ_j. If the SLQ_j is greater than or equal to 1 the regional coefficient is set to its national equivalent, otherwise the regional coefficient is set to the product of the multiplication with any shortfall assigned to imports. When an industry is absent from the region, but present nationally, the national coefficient is assigned in full to imports. Mayer and Pleeter (1975) offer theoretical justifications for the use of location quotients.

Other Location Quotient Methodologies

Several location quotient derivatives have targeted, with only limited success, the major shortcomings of the SLQ approach. These include the Purchases Only Location Quotient, the Cross-Industry Location Quotient, and the Logarithmic Cross-Industry Location Quotient. For a complete description of these approaches refer to Richardson (1972, p.118-122).

D.1.2 The Commodity Balance Approaches

The Supply-Demand Pool (SDP) method is most frequently utilised commodity-balance approach. For each industry the SDP method subtracts total regional requirements from total regional outputs to obtain a net commodity surplus or deficit. If a surplus results, regional supply is sufficient to satisfy regional demand, and national coefficients may be substituted for regional coefficients. If a deficit occurs, regional supply is insufficient to satisfy regional demand, and imports from other regions will be required. In this case, regional coefficients are estimated as follows:

$$r_{ij} = a_{ij} \frac{\beta_i}{\beta_i^r} \qquad \text{(D.2)}$$

where *r* represents the regional coefficient in industry *j* row *i*, *a* the national coefficient for industry *j* row *i*, β_i total national inputs for industry *j*, and β_i^r total regional inputs of industry *j*. Comparisons between the SDP approach, other adaptation approaches, and actual regional coefficients have produced mixed results (see for example McMenamin and Haring, 1974, Morrison and Smith, 1974; Sawyer and Miller, 1983).

D.1.3 Constrained Matrix Techniques

A key characteristic of constrained matrix techniques is their iterative nature. The most commonly utilised constrained matrix technique is the $\hat{\mathbf{RAS}}$ technique (early application were undertaken by Stone and Brown (1962), Czamanski and Malizia (1969), and explicated by Bacharach (1965), modified by *inter alia* Morrison and Smith (1974), McMenamin and Haring (1974) and more recently by Dietzenbacher and Lahr (2001)). Interestingly, St Louis (1989) adapted the standard $\hat{\mathbf{RAS}}$ approach for use with commodity-by-industry tables[291]. Tables D.1 to D.6 provide a hypothetical example of the application of the $\hat{\mathbf{RAS}}$ technique. Table D.1 provides estimates of primary inputs, final demand and total input and output for each industry. Using these estimates it is possible to calculate, for each industry, intermediate input/output by subtracting primary inputs/final demand from total input/output e.g. total intermediate input for the primary sector would be calculated as 964 – 586 = 378.

Table D.1 Hypothetical Transactions Table (Target Year)

	Primary	Manufacturing	Services	Intermediate Demand	Final Demand	Gross Output
Primary				647	318	964
Manufacturing				1,575	1,893	3,468
Services				1,248	3,380	4,628
Intermediate Demand	378	1,826	1,265	3,470	5,590	9,060
Primary Input	586	1,641	3,363	5,590	1,314	6,904
Gross Input	964	3,468	4,628	9,060	6,904	15,964

Using a regional transactions table, it is then possible to calculate row ratios for intermediate demand by dividing total intermediate demand for each row industry in the target year by the sum of the total intermediate demand for each row industry in the base year e.g. for primary industry the ratio would be 647 ÷ 651 = 0.99368 (Table D.2). Each row element in Table D.2 is then multiplied by the corresponding row ratio e.g. 171 x 0.99368 = 170 (0 d.p.), 464 x 0.99368 = 461 (0 d.p.), and 16 x 0.99368 = 16 (0 d.p.).

[291] St Louis (1989, p.384) found that the modified commodity-by-industry $\hat{\mathbf{RAS}}$ "compared very favourably with the [inter-industry] Leontief $\hat{\mathbf{RAS}}$ ".

Table D.2 Hypothetical Transactions Table (Base Year)

	Primary	Manufacturing	Services	Intermediate Demand (a_1)	Intermediate Demand - Target Yr (b)	Ratio (b/a_1)
Primary	171	464	16	651	647	0.99368
Manufacturing	113	860	442	1,414	1,575	1.11363
Services	128	454	809	1,391	1,248	0.89757
Intermediate Demand	411	1,778	1,267	3,456	3,470	

The resulting values are transferred to Table D.3 and column ratios are then computed by dividing estimated total intermediate demand for each column industry in the target year by the total intermediate demand for each column industry e.g. for primary industry the ratio would be 378 ÷ 410 = 0.92308. Each column element in Table D.3 is then multiplied by the corresponding column ratio and transferred to Table D.4 e.g. 170 x 0.92308 = 157 (0 d.p.), 125 x 0.92308 = 116 (0 d.p.), and 115 x 0.92308 = 106 (0 d.p.).

Table D.3 Hypothetical Transactions Table (Target Year) – 1st Iteration

	Primary	Manufacturing	Services	Intermediate Demand - Target Yr
Primary	170	461	16	647
Manufacturing	125	957	492	1,575
Services	115	407	726	1,248
Total (c_1)	410	1,826	1,234	3,470
Inter Demand - Target Yr (d)	378	1,826	1,265	
Ratio (d/c_1)	0.92308	1.00019	1.02526	

Table D.4 Hypothetical Transactions Table (Target Year) – 2nd Iteration

	Primary	Manufacturing	Services	Total (a_2)	Intermediate Demand - Target Yr (b)	Ratio (b/a_2)
Primary	157	461	16	634	647	1.01981
Manufacturing	116	957	505	1,578	1,575	0.99811
Services	106	407	744	1,258	1,248	0.99238
Inter Demand - Target Yr	378	1,826	1,265	3,470	3,470	

In a similar manner Tables D.5 and D.6 are then derived. As successive iterations are performed the ratio values approach unity. After several iterations the results obtained are sufficient for practical purposes.

Table D.5 Hypothetical Transactions Table (Target Year) – 3rd Iteration

	Primary	Manufacturing	Services	Intermediate Demand - Target Yr
Primary	160	471	16	647
Manufacturing	115	956	504	1,575
Services	105	404	739	1,248
Total (c_2)	380	1,830	1,259	3,470
Inter Demand - Target Yr (d)	378	1,826	1,265	
Ratio (d/c_2)	0.99455	0.99769	1.00501	

Table D.6 Hypothetical Transactions Table (Target Year) – Final Iteration

	Primary	Manufacturing	Services	Total (a_3)	Intermediate Demand - Target Yr (b)	Ratio (b/a_3)
Primary	159	469	16	645	647	1.00291
Manufacturing	115	953	506	1,575	1,575	1.00020
Services	105	403	742	1,250	1,248	0.99825
Inter Demand - Target Yr	378	1,826	1,265	3,470	3,470	

Overall, the $\mathbf{R\hat{A}S}$ method depends crucially on the choice of, in the case of an inter-industry table, the pre-assigned **A** matrix on which the iterations are performed. Concerns with the $\mathbf{R\hat{A}S}$ technique have included its uniform substitution effect and the so-called 'ripple effect' (see Bates and Bacharach (1963)) whereby one erroneous estimate in the $\mathbf{R\hat{A}S}$ generates errors throughout the rest of the table.

D.2 Other Approaches

D.2.1 Regional Weights

Using employment, value added, or output data this technique computes regional weights, these weights in turn are used to assemble a highly disaggregated national transaction table into a more aggregate regional table. In comparison with transactions tables derived from survey based data this approach has not produced favourable results and is considered to be in the tentative stage of development.

D.2.2 Representative Regional Coefficients

Mandeville (1975) advocates the use of representative regional coefficients taken from the survey coefficients developed for regions with similar economic compositions. This method has two major drawbacks. Firstly, an analyst may experience extreme difficulty in finding representative regional coefficients from survey data. Secondly, careful consideration must be given to using representative regional coefficients as subtle differences can easily exist between differing regions.

Appendix E

Industry Definitions and Concordances

Table E.1 Industry Definitions

	Industry Description	ANZSIC Code
1	Other horticulture	A01110-A01130
2	Apple and pear growing	A01150
3	Kiwifruit growing	A01170
4	Other fruit growing	A01140, A01160, A01191-A01199
5	Mixed livestock and cropping	A01210-A01220, A01591-A01592
6	Sheep and beef cattle farming	A01230-A01250
7	Dairy cattle farming	A01300
8	Other farming	A01410-A01530, A01593-A01699
9	Services to agriculture, hunting and trapping	A02120-A02200
10	Forestry	A03010
11	Services to forestry	A03030
12	Logging	A03020
13	Fishing	A04110-A04200
14	Coal mining	B11010-B11020
15	Services to mining	B15140-B15200
16	Other mining and quarrying	B13110-B14200
17	Oil & gas extraction	B12000
18	Oil & gas exploration	B15110-B15120
19	Meat processing	C21110
20	Poultry processing	C21120
21	Bacon, ham and smallgood manufacturing	C21130
22	Dairy product manufacturing	C21210-C21290
23	Fruit and vegetable, oil and fat, cereal and flour manufacturing	C21300-C21520
24	Bakery, sugar and confectionery manufacturing	C21610-C21720
25	Seafood processing	C21730
26	Other food manufacturing	C21740-C21790
27	Soft drink, cordial and syrup manufacturing	C21810
28	Beer, wine, spirit and tobacco manufacturing	C21820-C21900
29	Textile manufacturing	C22110-C22390
30	Clothing manufacturing	C22400
31	Footwear manufacturing	C22500
32	Other leather product manufacturing	C22611-C22620
33	Log sawmilling and timber dressing	C23110-C23130
34	Other wood product manufacturing	C23210-C23290
35	Paper and paper product manufacturing	C23310-C23390
36	Printing and services to printing	C24110-C24130
37	Publishing and recorded media manufacturing	C24210-C24300
38	Petroleum refining	C25100
39	Petroleum & coal product manufacturing nec	C25200
40	Fertiliser manufacturing	C25310
41	Other industrial chemical manufacturing	C25320
42	Medicinal, detergent and cosmetic manufacturing	C25430, C25450-C25460
43	Other chemical product manufacturing	C25410-C25420, C25440, C25470-C25490
44	Rubber manufacturing	C25510-C25590
45	Plastic product manufacturing	C25610-C25660
46	Glass and glass product and ceramic manufacturing	C26100-C26290
47	Other non-metallic mineral product manufacturing	C26310-C26400
48	Basic metal manufacturing	C27110-C27330
49	Structural, sheet and fabricated metal product manufacturing	C27410-C27690
50	Motor vehicle and part manufacturing	C28110-C28190
51	Ship and Boat Building	C28210-C28220
52	Other transport equipment manufacturing	C28230-C28290
53	Photographic and scientific equipment manufacturing	C28310-C28390
54	Electronic equipment and appliance manufacturing	C28410-C28590
55	Agricultural machinery manufacturing	C28610
56	Other industrial machinery and equipment manufacturing	C28620-C28690
57	Prefabricated building manufacturing	C29110-C29190
58	Furniture manufacturing	C29210-C29290
59	Other manufacturing	C29410-C29490
60	Electricity	D36100
61	Gas supply	D36200
62	Water supply	D37010

Table E.1 Industry Definitions (Continued)

	Industry Description	ANZSIC Code
63	Residential building construction (incl owner builders)	E41110-E41120
64	Non-residential building construction	E41130
65	Non-building construction	E41210-E41220
66	Site preparation services	E42100
67	Building structure services	E42210-E42240
68	Plumbing services	E42310
69	Installation trade services	E42320-E42340
70	Building completion services	E42410-E42450
71	Other construction services	E42510-E42590
72	Wholesale trade	F45110-F47990
73	Retail trade	G51101-G53290
74	Accommodation	H57100-H57109
75	Bars, clubs, cafes and restaurants	H57200-H57400
76	Road Freight transport	I61100
77	Road passenger transport	I61210-I61230, I66110-I66190
78	Water and rail transport	I62000-I63030, I66210-I66290
79	Air transport, services to transport and storage	I64010-I65090, I66300-I67090
80	Communication services	J71110-J71200
81	Finance	K73100-K73400
82	Life insurance	K74110
83	Superannuation fund operation	K74120
84	Health insurance	K74210
85	General insurance	K74220
86	Services to finance and insurance	K75110-K75200
87	Residential property operators	L77110-L77119
88	Commercial property operators	L77120-L77129
89	Real estate agents	L77200
90	Ownership of owner-occupied dwellings	N/A
91	Investors in other property	L77300-L77309
92	Vehicle and equipment hire	L77410-L77430
93	Scientific research	L78100
94	Technical services	L78210-L78290
95	Computer services	L78310-L78340
96	Legal services	L78410
97	Accounting services	L78420
98	Advertising and marketing services	L78510-L78530
99	Business administrative and management services	L78540-L78550
100	Employment, security and investigative services	L78610-L78640
101	Pest control and cleaning services	L78650-L78660
102	Other business services	L78670-L78690
103	Central government administration	M81110, M81300
104	Defence	M82000
105	Public order and safety services	M81200, Q96310-Q96330
106	Local government administration services and civil defence	M81130
107	Pre-school education	N84100
108	Primary and secondary education	N84210-N84240
109	Post school education	N84310-N84320
110	Other education	N84400
111	Hospitals and nursing homes	O86110-O86130
112	Medical, dental and other health services	O86210-O86390
113	Veterinary services	O86400
114	Child care services	O87100
115	Accommodation for the aged	O87210
116	Other community care services	O87220-O87290
117	Motion picture, radio and TV services	P91110-P91220
118	Libraries, museums and the arts	P92100-P92590
119	Horse and dog racing	P93110-P93112
120	Lotteries, casinos and other gambling	P93210-P93290
121	Other sport and recreational services	P93120-P93190, P93300
122	Personal and other community services	Q95110-Q96290, Q97000
123	Waste disposal, sewerage and drainage services	D37020, Q96340

Table E.2 Industry Definitions Concordance

123 Industry Description	48 Industry Description	35 Industry Description	23 Industry Description
1 Other horticulture	1 Horticulture and fruit growing	1 Horticulture and fruit growing	1 Agriculture
2 Apple and pear growing	1 Horticulture and fruit growing	1 Horticulture and fruit growing	1 Agriculture
3 Kiwifruit growing	1 Horticulture and fruit growing	1 Horticulture and fruit growing	1 Agriculture
4 Other fruit growing	1 Horticulture and fruit growing	1 Horticulture and fruit growing	1 Agriculture
5 Mixed livestock and cropping	2 Livestock and cropping farming	2 Livestock and cropping farming	1 Agriculture
6 Sheep and beef cattle farming	2 Livestock and cropping farming	2 Livestock and cropping farming	1 Agriculture
7 Dairy cattle farming	3 Dairy cattle farming	3 Dairy cattle farming	1 Agriculture
8 Other farming	4 Other farming	4 Other farming	1 Agriculture
9 Services to agriculture, hunting and trapping	5 Services to agriculture, hunting and trapping	5 Services to agriculture, hunting and trapping	1 Agriculture
10 Forestry	6 Forestry and logging	6 Forestry and logging	3 Forestry and logging
11 Services to forestry	6 Forestry and logging	6 Forestry and logging	3 Forestry and logging
12 Logging	6 Forestry and logging	6 Forestry and logging	3 Forestry and logging
13 Fishing	7 Fishing	7 Fishing	2 Fishing
14 Coal mining	8 Mining and quarrying	8 Mining, quarrying, oil and gas exploration and extraction	4 Mining and quarrying, oil and gas exploration and extraction
15 Services to mining	8 Mining and quarrying	8 Mining, quarrying, oil and gas exploration and extraction	4 Mining and quarrying, oil and gas exploration and extraction
16 Other mining and quarrying	8 Mining and quarrying	8 Mining, quarrying, oil and gas exploration and extraction	4 Mining and quarrying, oil and gas exploration and extraction
17 Oil & gas extraction	9 Oil and gas exploration and extraction	8 Mining, quarrying, oil and gas exploration and extraction	4 Mining and quarrying, oil and gas exploration and extraction
18 Oil & gas exploration	9 Oil and gas exploration and extraction	8 Mining, quarrying, oil and gas exploration and extraction	4 Mining and quarrying, oil and gas exploration and extraction
19 Meat processing	10 Meat and meat product manufacturing	9 Meat and meat product manufacturing	5 Food, beverages and tobacco manufacturing
20 Poultry processing	10 Meat and meat product manufacturing	9 Meat and meat product manufacturing	5 Food, beverages and tobacco manufacturing
21 Bacon, ham and smallgood manufacturing	10 Meat and meat product manufacturing	9 Meat and meat product manufacturing	5 Food, beverages and tobacco manufacturing
22 Dairy product manufacturing	11 Dairy product manufacturing	10 Dairy product manufacturing	5 Food, beverages and tobacco manufacturing
23 Fruit and vegetable, oil and fat, cereal and flour manufacturing	12 Other food manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
24 Bakery, sugar and confectionery manufacturing	12 Other food manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
25 Seafood processing	12 Other food manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
26 Other food manufacturing	12 Other food manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
27 Soft drink, cordial and syrup manufacturing	13 Beverage, malt and tobacco manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
28 Beer, wine, spirit and tobacco manufacturing	13 Beverage, malt and tobacco manufacturing	11 Other food, beverage, malt and tobacco manufacturing	5 Food, beverages and tobacco manufacturing
29 Textile manufacturing	14 Textile and apparel manufacturing	12 Textile and apparel manufacturing	6 Textile and apparel manufacturing
30 Clothing manufacturing	14 Textile and apparel manufacturing	12 Textile and apparel manufacturing	6 Textile and apparel manufacturing
31 Footwear manufacturing	14 Textile and apparel manufacturing	12 Textile and apparel manufacturing	6 Textile and apparel manufacturing
32 Other leather product manufacturing	14 Textile and apparel manufacturing	12 Textile and apparel manufacturing	6 Textile and apparel manufacturing
33 Log sawmilling and timber dressing	15 Wood product manufacturing	13 Wood, paper and paper product manufacturing	7 Wood product manufacturing
34 Other wood product manufacturing	15 Wood product manufacturing	13 Wood, paper and paper product manufacturing	7 Wood product manufacturing
35 Paper and paper product manufacturing	16 Paper and paper product manufacturing	13 Wood, paper and paper product manufacturing	8 Paper, paper products, printing, publishing and recorded media manufacturing
36 Printing and services to printing	17 Printing , publishing and recorded media	14 Printing, publishing and recorded media	8 Paper, paper products, printing, publishing and recorded media manufacturing
37 Publishing and recorded media manufacturing	17 Printing , publishing and recorded media	14 Printing, publishing and recorded media	8 Paper, paper products, printing, publishing and recorded media manufacturing
38 Petroleum refining	18 Petroleum and industrial chemical manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
39 Petroleum & coal product manufacturing nec	18 Petroleum and industrial chemical manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
40 Fertiliser manufacturing	18 Petroleum and industrial chemical manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
41 Other industrial chemical manufacturing	18 Petroleum and industrial chemical manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing

Table E.2 Industry Definitions Concordance (Continued)

123 Industry Description	48 Industry Description	35 Industry Description	23 Industry Description
42 Medicinal, detergent and cosmetic manufacturing	19 Rubber, plastic and other chemical product manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
43 Other chemical product manufacturing	19 Rubber, plastic and other chemical product manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
44 Rubber manufacturing	19 Rubber, plastic and other chemical product manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
45 Plastic product manufacturing	19 Rubber, plastic and other chemical product manufacturing	15 Petroleum, rubber, plastic and other chemical product manufacturing	9 Petroleum, chemical, rubber and plastic product manufacturing
46 Glass and glass product and ceramic manufacturing	20 Non-metallic mineral product manufacturing	16 Non-metallic mineral product manufacturing	10 Non-matellic mineral product manufacturing
47 Other non-metallic mineral product manufacturing	20 Non-metallic mineral product manufacturing	16 Non-metallic mineral product manufacturing	10 Non-matellic mineral product manufacturing
48 Basic metal manufacturing	21 Basic metal manufacturing	17 Basic metal manufacturing	11 Basic metal manufacturing
49 Structural, sheet and fabricated metal product manufacturing	22 Structural, sheet, and fabricated metal product manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
50 Motor vehicle and part manufacturing	23 Transport equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
51 Ship and Boat Building	23 Transport equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
52 Other transport equipment manufacturing	23 Transport equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
53 Photographic and scientific equipment manufacturing	24 Machinery and equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
54 Electronic equipment and appliance manufacturing	24 Machinery and equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
55 Agricultural machinery manufacturing	24 Machinery and equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
56 Other industrial machinery and equipment manufacturing	24 Machinery and equipment manufacturing	18 Other manufacturing	12 Structural, sheet, fabricated metal, transport, machinery and equipment product manufacturing
57 Prefabricated building manufacturing	25 Furniture and other manufacturing	18 Other manufacturing	13 Other Manufacturing
58 Furniture manufacturing	25 Furniture and other manufacturing	18 Other manufacturing	13 Other Manufacturing
59 Other manufacturing	25 Furniture and other manufacturing	18 Other manufacturing	13 Other Manufacturing
60 Electricity	26 Electricity generation and supply	19 Electricity generation and supply	14 Electricity, gas and water
61 Gas supply	27 Gas supply	20 Gas supply	14 Electricity, gas and water
62 Water supply	28 Water supply	21 Water supply	14 Electricity, gas and water
63 Residential building construction (incl owner builders)	29 Construction	22 Construction	15 Construction
64 Non-residential building construction	29 Construction	22 Construction	15 Construction
65 Non-building construction	29 Construction	22 Construction	15 Construction
66 Site preparation services	29 Construction	22 Construction	15 Construction
67 Building structure services	29 Construction	22 Construction	15 Construction
68 Plumbing services	29 Construction	22 Construction	15 Construction
69 Installation trade services	29 Construction	22 Construction	15 Construction
70 Building completion services	29 Construction	22 Construction	15 Construction
71 Other construction services	29 Construction	22 Construction	15 Construction
72 Wholesale trade	30 Wholesale trade	23 Wholesale and retail trade, accomodation, restaurants and bars	16 Wholesale and retail trade, accommodation, restaurants and bars
73 Retail trade	31 Retail trade	23 Wholesale and retail trade, accomodation, restaurants and bars	16 Wholesale and retail trade, accommodation, restaurants and bars
74 Accommodation	32 Accommodation, restaurants and bars	23 Wholesale and retail trade, accomodation, restaurants and bars	16 Wholesale and retail trade, accommodation, restaurants and bars
75 Bars, clubs, cafes and restaurants	32 Accommodation, restaurants and bars	23 Wholesale and retail trade, accomodation, restaurants and bars	16 Wholesale and retail trade, accommodation, restaurants and bars
76 Road Freight transport	33 Road transport	24 Transport and storage	17 Transport and storage
77 Road passenger transport	33 Road transport	24 Transport and storage	17 Transport and storage
78 Water and rail transport	34 Water and rail transport	24 Transport and storage	17 Transport and storage
79 Air transport, services to transport and storage	35 Air transport, services to transport and storage	24 Transport and storage	17 Transport and storage
80 Communication services	36 Communication services	25 Communication services	18 Communication services
81 Finance	37 Finance	26 Finance and insurance	19 Finance, insurance, real estate and business services
82 Life insurance	38 Insurance	26 Finance and insurance	19 Finance, insurance, real estate and business services

Table E.2 Industry Definitions Concordance (Continued)

123 Industry Description	48 Industry Description	35 Industry Description	23 Industry Description
83 Superannuation fund operation	38 Insurance	26 Finance and insurance	19 Finance, insurance, real estate and business services
84 Health insurance	38 Insurance	26 Finance and insurance	19 Finance, insurance, real estate and business services
85 General insurance	38 Insurance	26 Finance and insurance	19 Finance, insurance, real estate and business services
86 Services to finance and insurance	39 Services to finance and investment	26 Finance and insurance	19 Finance, insurance, real estate and business services
87 Residential property operators	40 Real estate	27 Real estate	19 Finance, insurance, real estate and business services
88 Commercial property operators	40 Real estate	27 Real estate	19 Finance, insurance, real estate and business services
89 Real estate agents	40 Real estate	27 Real estate	19 Finance, insurance, real estate and business services
90 Ownership of owner-occupied dwellings	41 Ownership of owner-occupied dwellings	28 Ownership of owner-occupied dwellings	20 Ownership of owner-occupied dwellings
91 Investors in other property	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
92 Vehicle and equipment hire	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
93 Scientific research	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
94 Technical services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
95 Computer services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
96 Legal services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
97 Accounting services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
98 Advertising and marketing services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
99 Business administrative and management services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
100 Employment, security and investigative services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
101 Pest control and cleaning services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
102 Other business services	42 Business services	29 Business services including equipment hire	19 Finance, insurance, real estate and business services
103 Central government administration	43 Central government administration, defence, public order and safety services	30 Central government administration, defence, public order and safety services	22 Central government administration, defence, public order and safety services
104 Defence	43 Central government administration, defence, public order and safety services	30 Central government administration, defence, public order and safety services	22 Central government administration, defence, public order and safety services
105 Public order and safety services	43 Central government administration, defence, public order and safety services	30 Central government administration, defence, public order and safety services	22 Central government administration, defence, public order and safety services
106 Local government administration services and civil defence	44 Local government administration services and civil defence	31 Local government administration services and civil defence	23 Local government administration services and civil defence
107 Pre-school education	45 Education	32 Education	21 Community, social and personal srvcs
108 Primary and secondary education	45 Education	32 Education	21 Community, social and personal srvcs
109 Post school education	45 Education	32 Education	21 Community, social and personal srvcs
110 Other education	45 Education	32 Education	21 Community, social and personal srvcs
111 Hospitals and nursing homes	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
112 Medical, dental and other health services	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
113 Veterinary services	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
114 Child care services	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
115 Accommodation for the aged	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
116 Other community care services	46 Health and community services	33 Health and community services	21 Community, social and personal srvcs
117 Motion picture, radio and TV services	47 Cultural and recreational services	34 Cultural and recreational services	21 Community, social and personal srvcs
118 Libraries, museums and the arts	47 Cultural and recreational services	34 Cultural and recreational services	21 Community, social and personal srvcs
119 Horse and dog racing	47 Cultural and recreational services	34 Cultural and recreational services	21 Community, social and personal srvcs
120 Lotteries, casinos and other gambling	47 Cultural and recreational services	34 Cultural and recreational services	21 Community, social and personal srvcs
121 Other sport and recreational services	47 Cultural and recreational services	34 Cultural and recreational services	21 Community, social and personal srvcs
122 Personal and other community services	48 Personal and other community services	35 Personal and other community services	21 Community, social and personal srvcs
123 Waste disposal, sewerage and drainage services	48 Personal and other community services	35 Personal and other community services	21 Community, social and personal srvcs

Table E.3 Commodity Definitions

Commodity Description	ANZSCC Code
1 Vegetables	012
2 Pipfruit	013.15
3 Kiwifruit	013.18.16
4 Other fruit and nuts	013.11-013.14, 013.16, 013.17, 013.18.11-013.18.15, 013.18.17-013.18.26, 013.20-013.40
5 Oil seeds	014
6 Plants, flowers, seeds	015
7 Raw vegetable materials	019
8 Sheep	021.15
9 Cattle	021.11, 021.12.01, 021.12.02
10 Wool	029.12
11 Grain and other crops	011
12 Beverage and spice crops	016, 018
13 Unmanufactured tobacco	017
14 Raw milk	No corresponding ANZSCC
15 Pigs	021.13
16 Poultry	021.14
17 Deer	021.16.13
18 Other livestock	021.16.11, 021.16.12, 021.16.14-021.16.90
19 Other animal products	029.11, 029.14-029.90
20 Agriculture services	881.10-881.30
21 Forestry and logging	031
22 Natural gums	032
23 Standing timber	No corresponding ANZSCC
24 Other forestry products	039
25 Services to forestry	881.40
26 Fish	041, 049
27 Crustaceans	042
28 Fishing services	882
29 Fishing quota leases	892.90
30 Coal	110
31 Metal ores	14
32 Building stone	151
33 Gypsum and limestone	152
34 Sand, pebbles, gravel, clay	153, 154
35 Chemical and fertilizer minerals	161
36 Salt	162
37 Precious metals and stones	163
38 Services incidental to mining	883
39 Capitalised exploration	No corresponding ANZSCC
40 Crude petroleum and natural gas	120
41 Capitalised oil and gas exploration	No corresponding ANZSCC
42 Meat and meat products	211.11, 211.12, 211.15-211.18, 211.24, 211.25, 211.27 03, 211.28-211.31, 211.34-211.37, 211.41, 211.43, 211.44
43 Poultry products	211.21-211.23, 211.42
44 Bacon, ham and smallgood products	211.13, 211.14, 211.26, 211.27.01, 211.27.02, 211.33, 211 38
45 Hides and skins	029.13
46 Processed milk and cream	221
47 Yoghurt, buttermilk, icecream	229.13, 229.14, 229.18
48 Other dairy products	229.11, 229.12, 229.15-229.17, 229.21-229.23
49 Prepared fish	211.32, 212
50 Prepared vegetables	213
51 Fruit juices	214
52 Prepared fruit and nuts	215
53 Oils and fats	216-218
54 Grain products	231
55 Starches	232
56 Animal feedings	233
57 Bakery products	234
58 Sugar	235
59 Confectionery	236
60 Macaroni and noodles	237
61 Other food products	239
62 Spirits, wines, beer, tobacco	241-243, 250
63 Soft drinks, bottled water	244
64 Natural textiles	261.01
65 Cotton textiles	261.90
66 Man-made fibres and textiles	262, 355
67 Yarn and thread	263, 264
68 Woven fabrics	265-268
69 Other textiles	271, 279
70 Carpets	272

Table E.3 Commodity Definitions (Continued)

Commodity Description	ANZSCC Code
71 Twine, rope, netting	273
72 Tanned skins and leather	283-291
73 Knitted fabrics	281
74 Clothing	282
75 Handbags and articles of leather	292
76 Footwear	297
77 Wood	311-313
78 Panels and boards	314
79 Veneer sheets and plywood	315
80 Builders joinery	316
81 Wood containers	317
82 Other wood products	319
83 Pulp, paper and paperboard	321
84 Non metal wastes and scraps	392
85 Books and stationery	322-326
86 Prepared printing plates	327
87 Newspapers and journals	328
88 Petroleum products	331-335
89 Industrial chemicals	336-345
90 Other chemical products	354, 391
91 Plastics	347, 363-369, 372
92 Rubber	348, 362
93 Rubber tyres	361
94 Paints	351
95 Pharmaceutical products	352
96 Soap and perfumes	353
97 Fertilisers	346.01-346.08
98 Pesticides	346.09
99 Glass and glass products	371, 373
100 Cement, lime and plaster	374
101 Articles of concrete and stone	375, 376
102 Other mineral products	379
103 Metal wastes	393
104 Iron and steel	411
105 Other metals	413-416
106 Structural metal products	412, 421
107 Tanks, reservoirs and containers	422
108 Steam generators	423
109 Other fabricated metal products	429
110 Engines	431
111 Motor vehicles and parts	491
112 Coachwork	492
113 Ships	493
114 Pleasure and sporting boats	494
115 Other transport equipment	495, 499
116 Aircraft and parts	496
117 General industrial machinery	432-439, 442, 443
118 Machinery for textile production	446
119 Agricultural and forestry equipment	441
120 Machinery for mining	444
121 Machinery for food production	445
122 Domestic appliances	448
123 Office equipment	449-451
124 Computers and parts	452
125 Electric equipment	461-474
126 Audio and video records and tapes	475
127 Watches and clocks	484
128 Medical equipment	481
129 Photographic and scientific equipment	482, 482
130 Furniture	381
131 Jewellery	382
132 Musical instruments	383
133 Sports goods	384
134 Games and toys	385, 386
135 Prefabricated buildings	387
136 Other manufactured articles	389, 447
137 Services incidental to manufacturing	884, 885
138 Electricity	171
139 Services incidental to electricity distribution	887
140 Water	173-180

Table E.3 Commodity Definitions (Continued)

Commodity Description	ANZSCC Code
141 Pre-erection work	511
142 Residential building construction	512.01-512.03, 521.01
143 Non-residential building construction	512.04, 512.05, 521.02
144 Civil engineering	513, 518, 522
145 Prefabricated constructions	514
146 Other installation work	515
147 Plumbing	516.12, 516.13
148 Electrical installation work	516.11, 516.14, 516.90
149 Fencing	516.15, 516.16
150 Building completion work	517
151 Land and land improvements	532-539
152 Wholesale trade	621, 622
153 Retail trade	631, 632
154 Repair services to machinery and equipment	611.03, 612.91-612.99, 633, 886
155 Accommodation	641
156 Meal services	642.10.01, 642.90
157 Takeaways	642.10.02
158 Beverage services	643
159 Road passenger transport	712.11-712.20
160 Road freight transport	712.30-712.40
161 Supporting services for road transport	744
162 Sea, water and rail services	711, 721, 722, 743, 745
163 Air transport, other transport and storage services	713.10, 731-742, 746-749
164 Communication services	751-754
165 Finance	811, 813
166 Life insurance	812.11
167 Superannuation services	812.12
168 Health insurance	812.21
169 General insurance	812.29
170 Services to finance and insurance	814
171 Leased commercial property services	821.20
172 Leased residential property services	821.10
173 Other real estate services	822
174 Owner-occupied dwellings	821.10
175 Equipment hire	831
176 Computer software and services	841-849, 892.11
177 Legal services	861
178 Accounting services	862
179 Taxation services	863
180 Architectural and engineering services	867
181 Advertising and marketing	864, 871, 892.12
182 Management consultancy	865, 866
183 Research and development	851-853
184 Placement and supply of personnel	872
185 Investigation and security services	873
186 Cleaning	874
187 Photographic services	875
188 Other business services	876-879
189 Central government administration services	911.11, 911.20-912.50, 912.70, 912.90-913.40
190 Public order, safety and defence	912.60, 912.61, 912.80
191 Local government administration services	911.12, 911.13
192 Preschool education	921.10
193 Primary education	921.90
194 Secondary education	922
195 Higher education	923
196 Other education services	924-929
197 Hospital and nursing care	931.11-931.13
198 Medical, dental and other health services	931.21-931.99
199 Vet services	932
200 Accommodation for the aged	933.11
201 Other social services	933.19, 933.29
202 Child care services	933.21
203 Motion picture, radio, TV services	961
204 News agency services	962
205 Libraries, museums, art	963
206 Sport and recreation services	964
207 Other personal and other community services	832, 940.40-959.90, 970-980
208 Sewerage services	940.10
209 Waste disposal	940.20-940.30
210 Direct purchases abroad by residents	No corresponding ANZSCC

Table E.4 Commodity Definitions Concordance

210 Commodity Description	64 Commodity Description	48 Commodity Description	35 Commodity Description
1 Vegetables	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
2 Pipfruit	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
3 Kiwifruit	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
4 Other fruit and nuts	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
5 Oil seeds	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
6 Plants, flowers, seeds	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
7 Raw vegetable materials	1 Horticulture and fruit	1 Horticulture and fruit	1 Horticulture and fruit
8 Sheep	2 Sheep	2 Sheep	2 Sheep
9 Cattle	3 Cattle	3 Cattle	3 Cattle
10 Wool	4 Wool	4 Wool	4 Wool
11 Grain and other crops	5 Grain and other crops	5 Grain and other crops	5 Grain and other crops
12 Beverage and spice crops	5 Grain and other crops	5 Grain and other crops	5 Grain and other crops
13 Unmanufactured tobacco	5 Grain and other crops	5 Grain and other crops	5 Grain and other crops
14 Raw milk	6 Raw milk	6 Raw milk	6 Raw milk
15 Pigs	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
16 Poultry	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
17 Deer	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
18 Other livestock	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
19 Other animal products	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
20 Agriculture services	8 Agriculture services	7 Other livestock and animal prdcts	7 Other livestock and animal prdcts
21 Forestry and logging	9 Forestry and logging	8 Forestry and logging	8 Forestry and logging
22 Natural gums	9 Forestry and logging	8 Forestry and logging	8 Forestry and logging
23 Standing timber	9 Forestry and logging	8 Forestry and logging	8 Forestry and logging
24 Other forestry products	9 Forestry and logging	8 Forestry and logging	8 Forestry and logging
25 Services to forestry	9 Forestry and logging	8 Forestry and logging	8 Forestry and logging
26 Fish	10 Fishing and fish products	9 Fishing and fish products	9 Fishing and fish products
27 Crustaceans	10 Fishing and fish products	9 Fishing and fish products	9 Fishing and fish products
28 Fishing services	10 Fishing and fish products	9 Fishing and fish products	9 Fishing and fish products
29 Fishing quota leases	10 Fishing and fish products	9 Fishing and fish products	9 Fishing and fish products
30 Coal	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
31 Metal ores	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
32 Building stone	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
33 Gypsum and limestone	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
34 Sand, pebbles, gravel, clay	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
35 Chemical and fertilizer minerals	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
36 Salt	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
37 Precious metals and stones	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
38 Services incidental to mining	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
39 Capitalised exploration	11 Mining and quarrying	10 Mining and quarrying	10 Mining and quarrying
40 Crude petroleum and natural gas	12 Oil and gas	11 Oil and gas	11 Oil and gas
41 Capitalised oil and gas explrtn	12 Oil and gas	11 Oil and gas	11 Oil and gas
42 Meat and meat products	13 Meat products	12 Meat products	12 Meat products
43 Poultry products	13 Meat products	12 Meat products	12 Meat products
44 Bacon, ham and smallgood products	13 Meat products	12 Meat products	12 Meat products
45 Hides and skins	13 Meat products	12 Meat products	12 Meat products
46 Processed milk and cream	14 Dairy products	13 Dairy products	13 Dairy products
47 Yoghurt, buttermilk, icecream	14 Dairy products	13 Dairy products	13 Dairy products
48 Other dairy products	14 Dairy products	13 Dairy products	13 Dairy products
49 Prepared fish	15 Other food	14 Other food	14 Other food
50 Prepared vegetables	15 Other food	14 Other food	14 Other food
51 Fruit juices	15 Other food	14 Other food	14 Other food
52 Prepared fruit and nuts	15 Other food	14 Other food	14 Other food
53 Oils and fats	15 Other food	14 Other food	14 Other food
54 Grain products	15 Other food	14 Other food	14 Other food
55 Starches	15 Other food	14 Other food	14 Other food
56 Animal feedings	15 Other food	14 Other food	14 Other food
57 Bakery products	15 Other food	14 Other food	14 Other food
58 Sugar	15 Other food	14 Other food	14 Other food
59 Confectionery	15 Other food	14 Other food	14 Other food
60 Macaroni and noodles	15 Other food	14 Other food	14 Other food
61 Other food products	15 Other food	14 Other food	14 Other food
62 Spirits, wines, beer, tobacco	16 Beverages and tobacco	15 Beverages and tobacco	15 Beverages and tobacco
63 Soft drinks, bottled water	16 Beverages and tobacco	15 Beverages and tobacco	15 Beverages and tobacco
64 Natural textiles	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
65 Cotton textiles	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
66 Man-made fibres and textiles	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
67 Yarn and thread	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
68 Woven fabrics	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
69 Other textiles	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
70 Carpets	17 Textiles	16 Textiles	16 Textiles, clothing and footwear

Table E.4 Commodity Definitions Concordance (Continued)

210 Commodity Description	64 Commodity Description	48 Commodity Description	35 Commodity Description
71 Twine, rope, netting	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
72 Tanned skins and leather	17 Textiles	16 Textiles	16 Textiles, clothing and footwear
73 Knitted fabrics	18 Clothing and footwear	17 Clothing and footwear	16 Textiles, clothing and footwear
74 Clothing	18 Clothing and footwear	17 Clothing and footwear	16 Textiles, clothing and footwear
75 Handbags and articles of leather	18 Clothing and footwear	17 Clothing and footwear	16 Textiles, clothing and footwear
76 Footwear	18 Clothing and footwear	17 Clothing and footwear	16 Textiles, clothing and footwear
77 Wood	19 Wood products	18 Wood products	17 Wood and paper products
78 Panels and boards	19 Wood products	18 Wood products	17 Wood and paper products
79 Veneer sheets and plywood	19 Wood products	18 Wood products	17 Wood and paper products
80 Builders joinery	19 Wood products	18 Wood products	17 Wood and paper products
81 Wood containers	19 Wood products	18 Wood products	17 Wood and paper products
82 Other wood products	19 Wood products	18 Wood products	17 Wood and paper products
83 Pulp, paper and paperboard	20 Paper products	19 Paper products	17 Wood and paper products
84 Non metal wastes and scraps	20 Paper products	19 Paper products	17 Wood and paper products
85 Books and stationery	21 Printing, pblshng & recorded media	20 Printing, pblshng & recorded media	17 Wood and paper products
86 Prepared printing plates	21 Printing, pblshng & recorded media	20 Printing, pblshng & recorded media	17 Wood and paper products
87 Newspapers and journals	21 Printing, pblshng & recorded media	20 Printing, pblshng & recorded media	17 Wood and paper products
88 Petroleum products	22 Petroleum products	21 Petroleum products	18 Ptrlm, chem, rubber & plastic prdcts
89 Industrial chemicals	23 Industrial chemicals	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
90 Other chemical products	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
91 Plastics	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
92 Rubber	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
93 Rubber tyres	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
94 Paints	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
95 Pharmaceutical products	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
96 Soap and perfumes	24 Rubber, plastic & othr chem prdcts	22 Chemical, rubber and plastic products	18 Ptrlm, chem, rubber & plastic prdcts
97 Fertilisers	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
98 Pesticides	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
99 Glass and glass products	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
100 Cement, lime and plaster	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
101 Articles of concrete and stone	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
102 Other mineral products	25 Non metallic mineral products	23 Non metallic mineral products	19 Non metallic mineral products
103 Metal wastes	26 Basic metals	24 Basic metals	20 Basic metals
104 Iron and steel	26 Basic metals	24 Basic metals	20 Basic metals
105 Other metals	26 Basic metals	24 Basic metals	20 Basic metals
106 Structural metal products	27 Strctrl, sheet & fbrctd metal prdcts	25 Strctrl, sheet & fbrctd metal prdcts	21 Fbrctd metal prdcts, mchnry & eqpmnt
107 Tanks, reservoirs and containers	27 Strctrl, sheet & fbrctd metal prdcts	25 Strctrl, sheet & fbrctd metal prdcts	21 Fbrctd metal prdcts, mchnry & eqpmnt
108 Steam generators	27 Strctrl, sheet & fbrctd metal prdcts	25 Strctrl, sheet & fbrctd metal prdcts	21 Fbrctd metal prdcts, mchnry & eqpmnt
109 Other fabricated metal products	27 Strctrl, sheet & fbrctd metal prdcts	25 Strctrl, sheet & fbrctd metal prdcts	21 Fbrctd metal prdcts, mchnry & eqpmnt
110 Engines	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
111 Motor vehicles and parts	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
112 Coachwork	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
113 Ships	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
114 Pleasure and sporting boats	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
115 Other transport equipment	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
116 Aircraft and parts	28 Motor vhcls & other trnsprt eqpmnt	26 Motor vhcls & other trnsprt eqpmnt	21 Fbrctd metal prdcts, mchnry & eqpmnt
117 General industrial machinery	29 Industrial machinery	27 Industrial machinery	21 Fbrctd metal prdcts, mchnry & eqpmnt
118 Machinery for textile production	29 Industrial machinery	27 Industrial machinery	21 Fbrctd metal prdcts, mchnry & eqpmnt
119 Agricultural and forestry equipment	29 Industrial machinery	27 Industrial machinery	21 Fbrctd metal prdcts, mchnry & eqpmnt
120 Machinery for mining	29 Industrial machinery	27 Industrial machinery	21 Fbrctd metal prdcts, mchnry & eqpmnt
121 Machinery for food production	29 Industrial machinery	27 Industrial machinery	21 Fbrctd metal prdcts, mchnry & eqpmnt
122 Domestic appliances	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
123 Office equipment	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
124 Computers and parts	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
125 Electric equipment	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
126 Audio and video records and	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
127 Watches and clocks	30 Electronic equipment and appliances	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
128 Medical equipment	31 Photographic & scientific eqpmnt	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
129 Photographic & scientific eqpmnt	31 Photographic & scientific eqpmnt	28 Elctrnc, phtgrphc, scntfc eqp & pplncs	21 Fbrctd metal prdcts, mchnry & eqpmnt
130 Furniture	32 Furniture	29 Furniture	22 Other manufactured products
131 Jewellery	33 Other manufactures	30 Other manufactures	22 Other manufactured products
132 Musical instruments	33 Other manufactures	30 Other manufactures	22 Other manufactured products
133 Sports goods	33 Other manufactures	30 Other manufactures	22 Other manufactured products
134 Games and toys	33 Other manufactures	30 Other manufactures	22 Other manufactured products
135 Prefabricated buildings	33 Other manufactures	30 Other manufactures	22 Other manufactured products
136 Other manufactured articles	33 Other manufactures	30 Other manufactures	22 Other manufactured products
137 Services incidental to mnfctrng	34 Services incidental to manufacturing	30 Other manufactures	22 Other manufactured products
138 Electricity	35 Electricity	31 Electricity	23 Electricity
139 Services incidental to electricity distribution	35 Electricity	31 Electricity	23 Electricity
140 Water	36 Water supply	32 Water supply	24 Water supply

Table E.4 Commodity Definitions Concordance (Continued)

210 Commodity Description	64 Commodity Description	48 Commodity Description	35 Commodity Description
141 Pre-erection work	37 Construction	33 Construction	25 Construction
142 Residential building cnstrctn	37 Construction	33 Construction	25 Construction
143 Non-residential building cnstrctn	37 Construction	33 Construction	25 Construction
144 Civil engineering	37 Construction	33 Construction	25 Construction
145 Prefabricated constructions	37 Construction	33 Construction	25 Construction
146 Other installation work	37 Construction	33 Construction	25 Construction
147 Plumbing	37 Construction	33 Construction	25 Construction
148 Electrical installation work	37 Construction	33 Construction	25 Construction
149 Fencing	37 Construction	33 Construction	25 Construction
150 Building completion work	37 Construction	33 Construction	25 Construction
151 Land and land improvements	37 Construction	33 Construction	25 Construction
152 Wholesale trade	38 Wholesale trade	34 Whlsle, retail trade & repair srvcs	26 Whlsle, retail trade & repair srvcs
153 Retail trade	39 Retail trade	34 Whlsle, retail trade & repair srvcs	26 Whlsle, retail trade & repair srvcs
154 Repair srvcs to machinery & eqpmnt	40 Repair srvcs to machinery & eqpmnt	34 Whlsle, retail trade & repair srvcs	26 Whlsle, retail trade & repair srvcs
155 Accommodation	41 Accmmdtn, rstmt & bar srvcs	35 Accmmdtn, rstmt & bar srvcs	27 Accmmdtn, rstmt & bar srvcs
156 Meal services	41 Accmmdtn, rstmt & bar srvcs	35 Accmmdtn, rstmt & bar srvcs	27 Accmmdtn, rstmt & bar srvcs
157 Takeaways	41 Accmmdtn, rstmt & bar srvcs	35 Accmmdtn, rstmt & bar srvcs	27 Accmmdtn, rstmt & bar srvcs
158 Beverage services	41 Accmmdtn, rstmt & bar srvcs	35 Accmmdtn, rstmt & bar srvcs	27 Accmmdtn, rstmt & bar srvcs
159 Road passenger transport	42 Road transport services	36 Road transport services	28 Road transport services
160 Road freight transport	42 Road transport services	36 Road transport services	28 Road transport services
161 Supporting srvcs for road transport	42 Road transport services	36 Road transport services	28 Road transport services
162 Sea, water and rail services	43 Water and rail transport services	37 Water and rail transport services	29 Water and rail transport services
163 Air transport, other transport and storage services	44 Air transport, other transport and storage services	38 Air transport, other transport and storage services	30 Air transport, other transport and storage services
164 Communication services	45 Communication services	39 Communication services	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
165 Finance	46 Finance services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
166 Life insurance	47 Insurance services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
167 Superannuation services	47 Insurance services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
168 Health insurance	47 Insurance services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
169 General insurance	47 Insurance services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
170 Services to finance and insurance	48 Services to finance and insurance	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
171 Leased commercial property srvcs	49 Real estate services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
172 Leased residential property services	49 Real estate services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
173 Other real estate services	49 Real estate services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
174 Owner-occupied dwellings	50 Owner-occupied dwellings	41 Owner-occupied dwellings	32 Owner-occupied dwellings
175 Equipment hire	51 Equipment hire services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
176 Computer software and services	52 Computer services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
177 Legal services	53 Legal and accounting services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
178 Accounting services	53 Legal and accounting services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
179 Taxation services	53 Legal and accounting services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
180 Architectural and engineering srvcs	54 Architectural and engineering services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
181 Advertising and marketing	55 Advertising and marketing services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
182 Management consultancy	56 Management consultancy services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
183 Research and development	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
184 Placement and supply of personnel	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
185 Investigation and security services	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
186 Cleaning	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
187 Photographic services	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
188 Other business services	57 Other business services	40 Fnnc, insurance & business srvcs	31 Cmmnctn, fnnc, insrnc & bsnss srvcs
189 Central government administration services	58 Central government administration and defence	42 Central government administration and defence	33 Central and local government
190 Public order, safety and defence	58 Central government administration and defence	42 Central government administration and defence	33 Central and local government
191 Local government administration services	59 Local government administration	43 Local government administration	33 Central and local government
192 Preschool education	60 Education	44 Education	34 Community services
193 Primary education	60 Education	44 Education	34 Community services
194 Secondary education	60 Education	44 Education	34 Community services
195 Higher education	60 Education	44 Education	34 Community services
196 Other education services	60 Education	44 Education	34 Community services
197 Hospital and nursing care	61 Health and community services	45 Health and community services	34 Community services
198 Medical, dental & other health srvcs	61 Health and community services	45 Health and community services	34 Community services
199 Vet services	61 Health and community services	45 Health and community services	34 Community services
200 Accommodation for the aged	61 Health and community services	45 Health and community services	34 Community services
201 Other social services	61 Health and community services	45 Health and community services	34 Community services
202 Child care services	61 Health and community services	45 Health and community services	34 Community services
203 Motion picture, radio, TV services	62 Culture and recreational services	46 Culture and recreational services	34 Community services
204 News agency services	62 Culture and recreational services	46 Culture and recreational services	34 Community services
205 Libraries, museums, art	62 Culture and recreational services	46 Culture and recreational services	34 Community services
206 Sport and recreation services	62 Culture and recreational services	46 Culture and recreational services	34 Community services
207 Other prsnl & other community srvcs	63 Prsnl & other community srvcs	47 Prsnl & other community srvcs	34 Community services
208 Sewerage services	63 Prsnl & other community srvcs	47 Prsnl & other community srvcs	34 Community services
209 Waste disposal	63 Prsnl & other community srvcs	47 Prsnl & other community srvcs	34 Community services
210 Direct purchases abroad by residents	64 Direct purchases abroad by residents	48 Direct purchases abroad by residents	35 Direct purchases abroad by residents

Appendix F

Aggregated Commodity-by-Industry Economic Input-Output Models for New Zealand and the Auckland Region, 1997-98

The commodity-by-industry economic input-output models for New Zealand and the Auckland Region have been aggregated from 48 commodities by 48 industries, as available in Excel format in the Chapter 5 directory of the accompanying CD-ROM, to 3 commodities by 3 industries for presentation purposes in this Appendix. Tables F.1 and F.2 respectively depict the commodity-by-industry input-outputs model for New Zealand and Auckland Region for the study year. Tables F.3 and F.4 respectively show industry-by-industry input-output models for New Zealand and Auckland Region as derived using the procedure described in Section 4.4.3.2.

Table F.1 Aggregated Commodity-by-Industry Input-Output Model for New Zealand, 1997-98 ($ mil)

	Commodities			Industries			Final Demands		Exports	Total Use
	Agriculture	Manufacturing	Service	Agriculture	Manufacturing	Service	Household Consumption	Other Final Demands		
Commodities										
- Agriculture				3,497	10,371	2,775	744	500	2,932	20,819
- Manufacturing				2,246	16,841	16,756	14,696	8,934	18,512	77,984
- Service				4,270	9,842	42,443	37,487	29,476	6,077	129,596
Industries										
- Agriculture	17,723	200	339							18,262
- Manufacturing	372	48,996	2,737							52,105
- Service	1,011	8,567	120,985							130,563
Value Added				8,248	15,051	68,589	6,410	1,128	296	99,723
Imports	1,713	20,222	5,535							27,469
Total Supply	20,819	77,984	129,596	18,262	52,105	130,563	59,337	40,038	27,817	556,521

Table F.2 Aggregated Commodity-by-Industry Input-Output Model for the Auckland Region, 1997-98 ($ mil)

	Commodities			Industries			Final Demands		Exports	Total Use
	Agriculture	Manufacturing	Service	Agriculture	Manufacturing	Service	Household Consumption	Other Final Demands		
Commodities										
- Agriculture				214	1,453	1,283	246	57	868	4,122
- *Manufacturing*				132	6,091	6,606	4,855	3,827	8,036	29,548
- Service				281	3,370	15,896	12,662	9,743	9,375	51,327
Industries										
- Agriculture	1,126	15	22							1,164
- Manufacturing	78	15,621	1,015							16,715
- Service	535	4,165	45,875							50,574
Value Added				537	5,800	26,789	2,118	352	94	35,690
Imports	2,382	9,747	4,414							16,543
Total Supply	4,122	29,548	51,327	1,164	16,715	50,574	19,881	13,979	18,372	205,683

Table F.3 Aggregated Industry-by-Industry Input-Output Model for New Zealand, 1997-98 ($ mil)

	Industries			Final Demands		Exports	Total Output
	Primary	Secondary	Tertiary	Household Consumption	Other Final Demands		
Industries							
- Agriculture	2,974	9,519	1,891	562	621	2,696	18,262
- Manufacturing	1,330	10,787	11,606	8,951	3,194	16,237	52,105
- Services	4,538	10,282	40,739	36,702	29,781	8,520	130,563
Value Added	8,248	15,051	68,589	6,410	1,128	296	99,723
Imports	1,172	6,466	7,737	6,712	5,314	0	27,401
Total Input	18,262	52,105	130,563	59,337	40,038	27,749	328,054

Table F.4 Aggregated Industry-by-Industry Input-Output Model for the Auckland Region, 1997-98 ($ mil)

	Industries			Final Demands		Exports	Total Output
	Primary	Secondary	Tertiary	Household Consumption	Other Final Demands		
Industries							
- Agriculture	38	280	114	47	25	660	1,164
- Manufacturing	53	3,180	3,439	2,362	1,252	6,428	16,715
- Services	294	3,345	14,932	12,058	8,807	11,139	50,574
Value Added	537	5,800	26,789	2,118	352	94	35,690
Imports	243	4,110	5,300	3,296	3,543	0	16,492
Total Input	1,164	16,715	50,574	19,881	13,979	18,321	120,635

Appendix G

Multiplier Analysis Methodology

This Appendix describes the calculation of output, value added and employment multipliers using inter-industry input-output tables.

G.1 Input-Output Multipliers

The starting point for calculating economic input-output multipliers is an industry-by-industry technical coefficients table. The technical coefficients Table G.1 represents the direct impact on each row industry *i* following a unit increase in output of any column industry *j*.

Table G.1 Technical Coefficients Table for a Hypothetical Region

	Primary	Manufacturing	Services	Household Consumption	Other Final Demand
Primary	0.1795	0.1414	0.0034	0.0065	0.0772
Manufacturing	0.1184	0.2619	0 0968	0.1839	0.3633
Services	0.1347	0.1382	0.1770	0.4629	0.4957
Value Added	0.0922	0.1526	0.3664		
Other Primary Inputs	0.4751	0.3059	0.3564	0.3467	0.0638
Total	1.0000	1.0000	1.0000	1.0000	1.0000

To account for indirect impacts it is necessary to subtract the intermediate demand technical coefficients from an identity matrix to obtain the Leontief matrix $(\mathbf{I} - \mathbf{A})$ (Table G.2), and then to invert the result to attain the Inverse Leontief Matrix $(\mathbf{I} - \mathbf{A})^{-1}$ (Table G.3). Each element in the inverse Leontief matrix indicates the total *direct* and *indirect* requirements from row industry *i* arising from a unit increase in sales to final demand by column industry *j*.

Table G.2 Leontief Matrix (I-A) for a Hypothetical Region

	Primary	Manufacturing	Services
Primary	0.8205	-0.1414	-0.0034
Manufacturing	-0.1184	0.7381	-0.0968
Services	-0.1347	-0.1382	0.8230

Table G.3 Leontief Inverse Matrix $(I-A)^{-1}$ for a Hypothetical Region

	Primary	Manufacturing	Services
Primary	1.2603	0.2479	0.0344
Manufacturing	0.2343	1.4314	0.1693
Services	0.2456	0.2810	1.2491
Total	1.7402	1.9603	1.4527

Closing the Leontief matrix with respect to household income and expenditure permits the calculation of not only *direct* and *indirect* effects, but also *induced* effects caused by consumer spending. This is achieved by subtracting not only the intermediate demand technical coefficients from an identity matrix but also the value added row and the household consumption column (Table G.4), and then inverting the result to gain $(\mathbf{I} - \mathbf{A}^*)^{-1}$ (Table G.5). Each element in the closed inverse Leontief matrix indicates the total direct, indirect and induced requirements from row industry i arising from a unit increase in sales to final demand by column industry j. In this way the value added row and the household consumption column are treated as industries, producing revenue and requiring inputs from other industries.

Table G.4 Closed Leontief Matrix $(I-A^*)$ for a Hypothetical Region

	Primary	Manufacturing	Services	Household Consumption
Primary	0.8205	-0.1414	-0.0034	-0.0065
Manufacturing	-0.1184	0.7381	-0.0968	-0.1839
Services	-0.1347	-0.1382	0.8230	-0.4629
Value Added	-0.0922	-0.1526	-0.3664	1.0000

Table G.5 Closed Leontief Inverse Matrix $(I-A^*)^{-1}$ for a Hypothetical Region

	Primary	Manufacturing	Services	Household Consumption
Primary	1.2840	0.2817	0.0822	0.0982
Manufacturing	0.3513	1.5978	0.4045	0.4834
Services	0.4609	0.5872	1.6820	0.8896
Value Added	0.3409	0.4850	0.6857	1.4088
Total	2.4371	2.9516	2.8544	2.8799

Input-output practitioners generally categorise multiplier effects into three groups, each of which represents a different view of the economy under study: output, value added and employment.

G.1.1 Output Multipliers

Output multipliers relate a unit of spending to an increase in output in the economy. A simple output multiplier for industry j can be found by summing the jth column of the Leontief inverse matrix (Table G.3). For example, a Type I (direct and indirect effect) multiplier for the manufacturing industry would be 0.2479+1.4314+0.2810=1.9603 (4 d.p.). Furthermore, a Type II (direct, indirect and induced effect) multiplier for industry j can be found by summing the jth column of the closed Leontief inverse matrix (Table G.5). For example, a total output multiplier for the manufacturing industry would be 0.2817+1.5978+0.5872+0.4850 =2.9517 (4 d.p.).

G.1.2 Value Added Multipliers

Value added multipliers show the relationship between an additional unit of spending and changes in the level of value added (i.e. wages and salaries, operating surplus, subsidies and the like). Underpinning value added multipliers is the notion that if an industry experiences a change in output there will be an associated variation in labour inputs and, in turn, variations in household consumption. A direct value added multiplier for column industry j is calculated as the value added technical coefficient for industry j. For example, a direct value added multiplier for the services industry would be 0.3664 (4 d.p.).

A direct and indirect value added multiplier for column industry j may be computed by summing the products of the elements in the Leontief inverse matrix for industry j and the supplying industry's value added technical coefficient. For example, the direct and indirect value added multiplier for the services industry would be $(0.0344 \times 0.0922)+(0.1693 \times 0.1526)+(1.2491 \times 0.3664)=0.4867$ (4 d.p.). It is necessary to sum household income changes over all industries as household consumption may vary in all industries to satisfy the change in demand for any industry's output.

A direct, indirect, and induced value added multiplier for column industry j may be obtained by taken the wages and salaries row coefficient of the closed Leontief inverse matrix for column industry j. For example, a direct, indirect and induced value added multiplier for the services industry would be 0.6857 (4 d.p.).

Using the preceding value added multipliers it becomes possible to calculate Type I and Type II value added multipliers. These multipliers measure the value added generated following a unit change in household expenditure for a given industry. The Type I value added multiplier is expressed as the ratio of the direct and indirect value added multiplier to the direct value added multiplier – resulting from a unit increase in final demand for a given industry. A Type I value added multiplier for the services industry would be 0.4867 ÷ 0.3664=1.3283 (4 d.p.).

The Type II multiplier attempts to explain induced effects initiated through consumer expenditure. This is measured by including the effect of household expenditure generated by value added made as the result of variations in demand in a given industry. The Type II multiplier is usually expressed as the ratio of the direct, indirect and induced value added multiplier to the direct value added multiplier – resulting from a unit increase in final demand for a given industry. A Type II value added multiplier for the services industry would be 0.6857 ÷ 0.3664=1.8715 (4 d.p.).

G.1.3 Employment Multipliers

Employment coefficients represent the number of people directly employed by the industry per unit of industry output. Mathematically, an employment coefficient may be expressed as:

$$\overline{empcoeff}_j = \frac{\overline{emp}'_j}{\beta'_j} \qquad \text{(G.1)}$$

where $\overline{empcoeff}_j$ represents the employment coefficient for industry j,

The substitution of the direct value added multiplier with an employment coefficient allows employment multipliers to be generated in the same fashion as value added multipliers. Type I and II employment multipliers gauge respectively the direct and indirect, and direct, indirect and induced employment impact associated with a change in direct employment in an industry. Such employment multipliers allow employment levels associated with increases in final demand in a given industry to be forecasted.

Appendix H

Aggregated Commodity-by-Industry Physical Input-Output Models for New Zealand and the Auckland Region, 1997-98

The commodity-by-industry physical input-output models for New Zealand and the Auckland Region have been aggregated from 48 commodities by 48 industries, as available in Excel format in the Chapter 6 directory of the accompanying CD-ROM, to 3 commodities by 3 industries for presentation purposes in this Appendix. Tables H.1 and H.2 respectively depict the physical input-output model for New Zealand and Auckland Region for the study year.

Table H.1 Aggregated Commodity-by-Industry Physical Input-Output Model for New Zealand, 1997-98 ('000s t)

	Commodities			Industries			Final consumption	Gross capital formation and man-made assets[1]	Exports
	Agriculture	Manufacturing	Service	Agriculture	Manufacturing	Service			
Commodities									
- Agriculture				7,563	40,725	13,786	1,672	9,802	9,456
- Manufacturing				3,767	14,799	13,775	5,872	783	9,723
- Service				1,976	78,417	309,919	207,402	217	35
Industries									
- Agriculture	72,119	493	0						
- Manufacturing	2,309	33,678	9						
- Service	3,380	7,961	597,474						
Final consumption expenditure									
Gross capital formation and man-made assets[1]									
Imports	5,195	6,587	482						
Raw Material Inputs									
- Soil excavation for structures									
- Water raised				421,210	211,376	259,819	1,303		
- Oxygen				12,036	13,210	11,262	7,090		
- Carbon dioxide				358,551			3,459		
- Other air components (nitrogen etc.)									
Residual Inputs									
- Wastes for economic re-use						243			
- Wastes for treatment, storage								6,416	
- Raw materials for energy carriers, not used									
- Waste water									
- Water vaporised									
- Other materials discharged into nature									
Gross Supply	83,004	48,719	597,966	805,103	358,526	608,804	226,799	17,217	19,213

Notes:
1. Man-made assets comprise controlled landfills.

Table H.1 Aggregated Commodity-by-Industry Physical Input-Output Model for New Zealand, 1997-98 ('000s t) (Continued)

	Raw Material Outputs					Residual Outputs						Materials Balance	Gross Use
	Soil excavation for structures	Water raised	Oxygen	Carbon dioxide	Other air components (nitrogen etc)	Wastes for economic re-use	Wastes for treatment, storage	Raw materials for energy carriers, not used	Waste water	Water vaporised	Other materials discharged into nature		
Commodities													
- Agriculture													83,004
- Manufacturing													48,719
- Service													597,966
Industries													
- Agriculture						0	5		595,228		5,786	131,471	805,103
- Manufacturing						57	1,089		462,319		15,301	-156,236	358,526
- Service						49	3,794		1,080,413		10,065	-1,094,332	608,804
Final consumption expenditure						137	1,527		197,570		6,096	21,469	226,799
Gross capital formation and man-made assets[1]									167			17,050	17,217
Imports												6,949	19,213
Raw Material Inputs													
- Soil excavation for structures													
- Water raised												-893,708	
- Oxygen												-43,598	
- Carbon dioxide												-362,010	
- Other air components (nitrogen etc.)													
Residual Inputs													
- Wastes for economic re-use													243
- Wastes for treatment, storage													6,416
- Raw materials for energy carriers, not used													
- Waste water												2,335,697	2,335,697
- Water vaporised													
- Other materials discharged into nature												37,248	37,248
Gross Supply						243	6,416		2,335,697		37,248		

Notes:
1. Man-made assets comprise controlled landfills.

Table H.2 Aggregated Commodity-by-Industry Physical Input-Output Model for the Auckland Region, 1997-98 ('000s t)

	Commodities			Industries			Final consumption	Gross capital formation and man-made assets[1]	Exports
	Agriculture	Manufacturing	Service	Agriculture	Manufacturing	Service			
Commodities									
- Agriculture				579	10,569	5,150	543	1,022	3,522
- Manufacturing				220	5,143	5,047	1,945	335	6,060
- Service				79	4,120	51,094	46,070	43	39
Industries									
- Agriculture	7,710	37	0						
- Manufacturing	976	10,601	4						
- Service	1,821	4,100	101,250						
Final consumption expenditure									
Gross capital formation and man-made assets[1]									
Imports	10,878	4,013	191						
Raw Material Inputs									
- Soil excavation for structures									
- Water raised				18,834	11,343	61,277	227		
- Oxygen				340	4,539	3,876	2,168		
- Carbon dioxide				8,340			850		
- Other air components (nitrogen etc.)									
Residual Inputs									
- Wastes for economic re-use						86			
- Wastes for treatment, storage								1,779	
- Raw materials for energy carriers, not used									
- Waste water									
- Water vaporised									
- Other materials discharged into nature									
Gross Supply	21,385	18,751	101,445	28,392	35,714	126,531	51,802	3,178	9,621

Notes:

1. Man-made assets comprise controlled landfills.

Table H.2 Aggregated Commodity-by-Industry Physical Input-Output Model for the Auckland Region, 1997-98 ('000s t) (Continued)

	Raw Material Outputs					Residual Outputs						Materials Balance	Gross Use
	Soil excavation for structures	Water raised	Oxygen	Carbon dioxide	Other air components (nitrogen etc)	Wastes for economic re-use	Wastes for treatment, storage	Raw materials for energy carriers, not used	Waste water	Water vaporised	Other materials discharged into nature		
Commodities													
- Agriculture													21,385
- Manufacturing													18,751
- Service													101,445
Industries													
- Agriculture						0	1		1,472		229	18,943	28,392
- Manufacturing						26	294		4,039		5,479	14,295	35,714
- Service						20	1,084		47,920		3,334	-32,998	126,531
Final consumption expenditure						41	400		43,644		1,864	5,853	51,802
Gross capital formation and man-made assets[1]									28			3,150	3,178
Imports												-5,461	9,621
Raw Material Inputs													
- Soil excavation for structures													
- Water raised												-91,681	
- Oxygen												-10,923	
- Carbon dioxide												-9,190	
- Other air components (nitrogen etc.)													
Residual Inputs													
- Wastes for economic re-use													86
- Wastes for treatment, storage													1,779
- Raw materials for energy carriers, not used													
- Waste water												97,104	97,104
- Water vaporised													
- Other materials discharged into nature												10,906	10,906
Gross Supply						86	1,779		97,104		10,906		

Notes:
1. Man-made assets comprise controlled landfills.

Appendix I

Raw Material and Residual Inputs/Outputs of the Auckland Region Economy, 1997-98

In this Appendix the raw material and residual inputs/outputs of the Auckland Region economy for the study year are discussed in detail. The Appendix is separated into four Sections, namely: raw material inputs, residual inputs, raw material outputs, and residual outputs. Refer to Table 4.2 for the dimensions of the matrices.

I.1 Raw Material Inputs

Raw material inputs (Table I.1) into industries and households are captured in matrices $\widetilde{\mathbf{K}}$ and $\widetilde{\mathbf{H}}$ respectively of the PIOT (refer Table I.2). These matrices include natural resource and ecosystem inputs such as water, oxygen and carbon dioxide.

Table I.1 Raw Material Inputs by 48 Industries and Households in the Auckland Region Economy, 1997-98 (000's t)

	Industry	Water raised	Oxygen	CO_2	Total
1	Hort & fruit growing	7,066.63 (2)	12.82	77.02	7,156.48
2	Livestock & cropping	1,210.53	149.19	3,858.82 (1)	5,218.54
3	Dairy cattle farming	4,137.16 (3)	69.31	2,647.12 (2)	6,853.59
4	Other farming	488.48	24.70	884.49 (3)	1,397.67
5	Srvcs to ag, hnt & trppng	11.82	10.15	0.00	21.97
6	Forestry & logging	0.00	10.34	872.22 (4)	882.56
7	Fishing	125.69	47.59	0.00	173.28
8	Mining & Quarrying	3,789.27	9.48	0.00	3,798.75
9	Oil & gas explr & extrc	2,004.63	6.03	0.00	2,010.66
10	Meat & meat prdct manuf	1,383.96	45.44	0.00	1,429.41
11	Dairy prdct manuf	3,818.88 (5)	273.67	0.00	4,092.55
12	Other food manuf	628.40	197.66	0.00	826.06
13	Bev, malt & tobacco manuf	1,584.22	75.59	0.00	1,659.81
14	Textile & apparel manuf	1,327.15	86.24	0.00	1,413.39
15	Wood prdct manuf	498.15	144.77	0.00	642.92
16	Paper & paper prdct manuf	0 00	1,611.40 (2)	0.00	1,611.40
17	Print, pub & rec media	55.20	15.45	0.00	70.64
18	Ptrlm & ind chem manuf	285.21	81.19	0.00	366.40
19	Rub, plstc & chm prdct mnf	55.49	139.20	0.00	194.70
20	Nn-mtllc mnrl prdct manuf	184.07	349.18	0.00	533.25
21	Basic metal manuf	982.00	1,244.00 (4)	0.00	2,226.00
22	Strctrl, sht & fb mtl prdct	0.00	59.32	0.00	59.32
23	Transport equip manuf	18.06	33.31	0.00	51.37
24	Machinery & equip manuf	168.68	76.15	0.00	244.83
25	Furniture & other manuf	353.45	106.52	0.00	459.97
26	Elctrcty gnrtn & spply	52,665.12 (1)	0.00	0.00	52,665.12
27	Gas supply	584.00	0.00	0.00	584.00
28	Water supply	0.00	10.15	0.00	10.15
29	Construction	0.00	236.00	0.00	236.00
30	Wholesale trade	18.28	462.07	0.00	480.34
31	Retail trade	267.88	400.65	0.00	668.53
32	Accom, restaurants & bars	360.68	96.36	0.00	457.04
33	Road transport	0.00	1,341.09 (3)	0.00	1,341.09
34	Water & rail trans	6.69	204.83	0.00	211.52
35	Air trns, srvcs trns & strg	3.65	557.53 (5)	0.00	561.18
36	Communication srvcs	0.00	68.56	0.00	68.56
37	Finance	0.00	24.88	0.00	24.88
38	Insurance	0.00	3.58	0.00	3.58
39	Srvcs to fnnce & invstmnt	0.00	3.73	0.00	3.73
40	Real estate	0.00	27.27	0.00	27.27
41	Ownership OOD	0.00	0.00	0.00	0.00
42	Business srvcs	200.52	82.63	0.00	283.15
43	Central government	109.15	110.00	0.00	219.15
44	Local government	2.00	5.63	0.00	7.63
45	Education	200.36	51.08	0.00	251.45
46	Health & community srvcs	334.18	112.74	0.00	446.93
47	Cultural & rec srvcs	4,044.13 (4)	30.41	0.00	4,074.54
48	Personal & other comm srvcs	2,480.30	46.62	0.00	2,526.92
49	FCE - Hshlds	226.53	2,168.28 (1)	850.22 (5)	3,245.03
	Total	91,680.59	10,922.81	9,189.90	111,793.30

Notes:
Figures in brackets indicate top five ranking.

Water raised. The figures for water raised in Table I.1 cover water extracted directly from the Auckland Region environment, not from the reticulation system, and therefore exclude water takes by the water supply [28] industry.[292] By far the largest water take of 52.6 million t (or 57.4 percent) was by the electricity generation and supply [26] industry, primarily for the operation of the Otahuhu Power Station. The primary industries of horticulture and fruit growing [1] and dairy cattle farming [3], both significant in the Auckland Region, were the second and third highest users of extracted water (7.1 million t and 4.1 million t respectively). Cultural and recreational services [47] was the fourth highest user, appropriating 4.0 million t of water mainly for upkeep of golf courses, other sports grounds, camping grounds, and parks and gardens. Water was extracted from three main river catchments, namely the Pahurehure, Northern Manukau and Wairoa catchments.

Oxygen. Oxygen in the Auckland Region is used primarily for combustion (98.6 percent of total oxygen used) and farm animal breathing. Households were the highest appropriators of oxygen (2.2 million t) for combustion purposes and motor vehicles, with industries such as paper and paper product manufacturing [16] (1.6 million t), mainly Penrose Pulp and Paper Mill, and basic metal manufacturing [21] (1.2 million t), primarily Glenbrook Steel Mill, the second and fourth largest oxygen users respectively. Auckland Region's large road transport [33] industry uses 1.3 million t of oxygen for road freight vehicles, buses and taxis. The largest amounts of oxygen for farm animal breathing were appropriated by the livestock and cropping farming [2] (0.13 million t) and dairy cattle farming [3] (0.05 million t) industries.

Carbon Dioxide. Carbon dioxide (CO_2) for photosynthesis is appropriated largely by the agricultural industries of livestock and cropping farming [2] (3.86 million t), dairy cattle farming [3] (2.65 million t) and other farming [4] (0.88 million t). Together these industries use more than 80.0 percent of CO_2 extracted from the Auckland Region environment. The extensive *Pinus Radiata* plantations in Rodney and Franklin Districts make the forestry and logging [6] industry the fourth highest appropriator of CO_2 for photosynthesis (0.87 million t), while vegetative cover on residential land is reflected in the 0.85 million t of CO_2 used by households.

I.2 Residual Inputs

Matrices $\tilde{\mathbf{E}}$ and $\tilde{\mathbf{D}}$ capture residual inputs, i.e. wastes for economic re-use and wastes for treatment and storage, into industries and capital formation respectively. Matrix $\tilde{\mathbf{E}}$ is sparsely

[292] Water as extracted by the water supply [28] industry is recorded as a commodity elsewhere in the PIOT.

populated, comprising economic residuals recycled from nature by industry, while matrix $\widetilde{\mathbf{D}}$ consists of, for example, recycled or reused solid waste from controlled landfills.

Wastes for Economic Re-use. This constitutes the recycled solid wastes of aluminium, glass, paper, plastic and steel. All 0.09 million t of recycled solid waste is used by personal and other community services [48] primarily through the waste disposal service, with paper making up the bulk of this at 0.06 million t (or 71.0 percent).

Wastes for Treatment, Storage. Landfill solid waste, such as construction and demolition waste, metal, glass, plastic, paper, potentially hazardous, organic matter, and other, and cleanfill solid waste, such as construction and demolition waste, are used as inputs into controlled landfills in the capital formation sector. Landfill and cleanfill solid wastes make up about half each of the total of 1.78 million t, with organic matter of 0.26 million t making up the largest component of landfill solid waste (28.1 percent).

I.3 Raw Material Outputs

Matrix $\widetilde{\mathbf{Q}}$ represents raw material outputs from industries and is sparsely populated, capturing renewable resource stock increases such as livestock, trees and some plant species. As these increases are negligible in the Auckland Region, no raw material outputs have been included in the PIOT.

I.4 Residual Outputs

Residuals generated by industries, households and capital formation (Table I.2) are captured in matrices $\widetilde{\mathbf{P}}$, $\widetilde{\mathbf{O}}$ and $\widetilde{\mathbf{L}}$ respectively. These comprise wastes for economic re-use, wastes for treatment and storage, waste water and other materials discharged into nature.

Table I.2 Residual Outputs by 48 Industries, Final Consumption, and Gross Capital Formation and Man-made Assets in the Auckland Region Economy, 1997-98 ('000s t)

Industry	Wastes for economic re-use	Wastes for treatment, storage		Waste water	Other materials discharged into nature						Total
	Solid waste	Solid waste			Water pollution		Air emissions				
	Recycled solid waste	Landfill solid waste	Cleanfill solid waste		Point-source water pollution	Non-point source water pollution	Energy use emissions	Non-energy industrial air emissions	Vegetation/land cover emissions	Farm animal emissions	
1 Hort & fruit growing	0.05	0.48	0.00	14.60	0.00	0.35 (4)	11.02	0 00	0.33 (5)	0.00	26.83
2 Livestock & cropping	0 00	0.24	0 00	340.43	0.06 (3)	1.63 (3)	14.92	0.00	22.41 (1)	24.29 (1)	403.97
3 Dairy cattle farming	0.00	0.26	0.00	1,028.58	0.21 (2)	4.95 (1)	17.25	0.00	9.79 (3)	12.85 (2)	1,073.89
4 Other farming	0.00	0.10	0.00	0.99	0.00	1.65 (2)	14.24	0.00	3.97 (4)	0.94 (3)	21.88
5 Srvcs to ag, hnt & trppng	0.00	0.05	0 00	15.75	0.00	0.00	8.72	0.00	0.00	0.00	24.53
6 Forestry & logging	0.00	0.00	0.00	1.23	0.00	0.05 (5)	8.89	0.00	13.11 (2)	0.00	23.28
7 Fishing	0 00	0.00	0 00	70.21	0.00	0.00	40.91	0.00	0 00	0.00	111.11
8 Mining & Quarrying	0.00	0.12	0.00	0.00	0.00	0.00	8.15	2.76	0.00	0.00	11.04
9 Oil & gas explr & extrc	0.00	0.00	0.00	0.00	0.00	0.00	5.18	0.00	0.00	0.00	5.18
10 Meat & meat prdct manuf	0.00	1.86	0 00	229.76	0.01	0.00	39 06	0.78	0 00	0.00	271.48
11 Dairy prdct manuf	0.03	10.49	0.00	1,227.78	0.00	0.00	235.27	11.42	0.00	0.00	1,484.99
12 Other food manuf	0.34	27.68	0.00	289.87	0.00	0.00	169.94	79.43 (3)	0.00	0.00	567.26
13 Bev, malt & tobacco manuf	1.45	13.63	0.00	159.15	0.00	0.00	64.98	0.00	0.00	0.00	239.22
14 Textile & apparel manuf	0.14	6.29	0.00	334.20	0.00	0.00	74.14	0.00	0.00	0.00	414.77
15 Wood prdct manuf	0.04	22.69	0.00	0.00	0.00	0.00	124.44	74.10 (4)	0 00	0.00	221.28
16 Paper & paper prdct manuf	8.03 (2)	24.25	0.00	0.00	0.00	0 00	1,384 94 (2)	7.08	0.00	0.00	1,424.30
17 Print, pub & rec media	6.98 (3)	12.73	0.00	0.00	0.00	0.00	13.28	0.00	0.00	0.00	32.99
18 Ptrlm & ind chem manuf	0.40	61.09 (4)	0.00	0.25	0 00	0 00	69.80	61.00 (5)	0.00	0.00	192.54
19 Rub, plstc & chm prdct mnf	2.58	40.71 (5)	0 00	0.00	0 00	0 00	119.67	0.00	0.00	0.00	162.96
20 Nn-mtllc mnrl prdct manuf	0.65	19.60	0.00	0.00	0.00	0.00	300.17	859.90 (1)	0 00	0.00	1,180.31
21 Basic metal manuf	0.61	4.29	0.00	1,400.00	0 00	0.00	1,069.34 (4)	0.10	0.00	0.00	2,474.34
22 Strctrl, sht & fb mtl prdct	1.58	17.60	0 00	82.33	0.00	0 00	51 00	0.13	0.00	0.00	152.65
23 Transport equip manuf	1.18	5.52	0.00	55.83	0 00	0.00	28.64	0.14	0.00	0.00	91.30
24 Machinery & equip manuf	1.44	11.27	0.00	260.26	0.00	0 00	65.46	0.12	0.00	0.00	338.55
25 Furniture & other manuf	0.31	14.52	0.00	0.00	0.00	0.00	91.56	483.38 (2)	0 00	0.00	589.76
26 Elctrcty gnrtn & spply	0.01	0.13	0.00	0 00	0 00	0.00	0.00	0.04	0.00	0.00	0.18
27 Gas supply	0.03	0.24	0 00	0.00	0.00	0.00	0 00	0.07	0.00	0.00	0.34
28 Water supply	0.19	1.05	0.00	33,706.52 (2)	0 00	0.00	8.73	0.11	0.00	0.00	33,716.61

Notes:
Figures in brackets indicate top five ranking.

Table I.2 Residual Outputs by 48 Industries, Final Consumption, and Gross Capital Formation and Man-made Assets in the Auckland Region Economy, 1997-98 ('000s t) (Continued)

Industry	Wastes for economic re-use	Wastes for treatment, storage		Waste water	Other materials discharged into nature						Total
	Solid waste	Solid waste			Water pollution		Air emissions				
	Recycled solid waste	Landfill solid waste	Cleanfill solid waste		Point-source water pollution	Non-point source water pollution	Energy use emissions	Non-energy industrial air emissions	Vegetation/land cover emissions	Farm animal emissions	
29 Construction	2.17	77.10 [2]	867.33 [1]	0.02	0.00	0.00	202.88	0.10	0.00	0.00	1,149.62
30 Wholesale trade	6.09 [4]	67.98 [3]	0.00	2,657.89 [4]	0.00	0.00	397.32	0.10	0 00	0.00	3,129.39
31 Retail trade	1.68	20.74	0.00	2,349.32 [5]	0.04 [4]	0.00	344.51	0.52	0.00	0 00	2,716.81
32 Accom, restaurants & bars	0.51	12.00	0.00	489.91	0.00	0.00	82.84	0.02	0.00	0.00	585.29
33 Road transport	0.53	5.07	0.00	143.68	0.00	0.00	1,153.02 [3]	0.01	0.00	0.00	1,302.32
34 Water & rail trans	0.02	0.13	0.00	111.08	0.00	0.00	176.08	0.07	0 00	0.00	287.38
35 Air trns, srvcs trns & strg	6.05 [5]	11.72	0.00	510.32	0.01	0.00	479.15 [5]	0.26	0.00	0.00	1,007.50
36 Communication srvcs	0.02	0.12	0.00	117.42	0.00	0 00	58.95	0.04	0 00	0.00	176.55
37 Finance	0.01	0.10	0.00	129.54	0.00	0.00	21.39	0.05	0.00	0.00	151.08
38 Insurance	0.00	0.01	0.00	38.27	0.00	0.00	3.08	0.06	0.00	0.00	41.42
39 Srvcs to fnnce & invstmnt	0.01	0.03	0.00	47.20	0 00	0 00	3.21	0.06	0.00	0.00	50.51
40 Real estate	0.12	0.52	0.00	121.05	0.00	0.00	23.44	0.08	0.00	0 00	145.21
41 Ownership OOD	0.09	0.65	0.00	0 00	0 00	0.00	0.00	0 00	0.00	0.00	0.74
42 Business srvcs	0.61	2.31	0.00	1,091.61	0.03 [5]	0.00	71.04	0.06	0 00	0 00	1,165.67
43 Central government	0.07	1.35	0.00	370.81	0.00	0 00	94.56	0.03	0.00	0.00	466.82
44 Local government	0.02	0.68	0.00	346.94	0.00	0.00	4.84	0.02	0.00	0.00	352.49
45 Education	0.20	1.96	0.00	447.42	0.00	0.00	43.91	0.02	0.00	0.00	493.51
46 Health & community srvcs	0.44	8.62	0.00	846.76	0.03	0.00	96.92	0.02	0.00	0.00	952.79
47 Cultural & rec srvcs	0.38	2.20	0.00	414.62	0.00	0 00	26.14	0.04	0 00	0.00	443.38
48 Personal & other comm srvcs	0.32	1.72	0.00	3,979.69 [3]	0.27 [1]	0.00	40.08	0.03	0.00	0.00	4,022.12
49 FCE - Hshlds	41.00 [1]	399.60 [1]	0 00	43,644.18 [1]	0.00	0.00	1,864.25 [1]	0.00	0.00	0.00	45,949.03
50 FCE - PNP instns srvng hshlds	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
51 FCE - Central govt	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52 FCE - Local govt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
53 GCF - Gross fixd captl frmtn	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
54 GCF - Chng in inventories	0.00	0.00	0.00	28.34	0.00	0.00	0.00	0.00	0.00	0.00	28.34
55 Man-made assets - Cntrld landfls	0.00	0.00	0.00	0.00	0.00	0.00	0 00	0.00	0.00	0 00	0.00
Total	86.41	911.50	867.33	97,103.81	0.66	8.63	9,227.29	1,582.17	49.62	38.08	109,875.50

Wastes for Economic Re-use. This constitutes the recycled solid wastes of aluminium, glass, paper, plastic and steel. Households are the highest producers of all recycled solid wastes at 0.04 million t (or 47.4 percent). Paper makes up the bulk of recycled solid waste at 0.06 million t (or 71.0 percent), with households providing almost half of this (0.03 million t). Glass constitutes 0.02 million t (or 17.6 percent), with households once again the largest contributors, providing 42.2 percent of total glass.

Wastes for Treatment, Storage. This comprises landfill solid waste, namely construction and demolition waste, metal, glass, plastic, paper, potentially hazardous waste, organic matter, and other wastes, and cleanfill solid waste, namely construction and demolition waste. Households are the largest providers of landfill solid waste at 0.40 million t (or 43.8 percent), with 0.17 million t of this being organic matter (kitchen and garden waste). The construction [29] and wholesale trade [30] industries are the second and third highest producers of landfill solid waste respectively, at 0.08 million t (mainly construction and demolition waste) and 0.07 million t (mainly potentially hazardous waste and organic matter). The construction [29] industry is responsible for all of the cleanfill solid waste of 0.87 million t.

Waste Water. Discharges of waste water in the Auckland Region amounted to 97.1 million t. Households produced the most waste water at 43.6 million t, while water supply [28] accounted for 33.7 million t largely from leakage. Personal and other community services [48], wholesale trade [30] and retail trade [31] are high producers of waste water, together accounting for nearly 10.0 percent of the total waste water discharged. Other notable water discharges in the Auckland Region are from basic metal manufacturing [21] (1.4 million t), largely from Glenbrook Steel Mill into the Waiuku River, and the dairy industry, with 1.23 million t from dairy products manufacturing [11] and 1.03 million t from dairy cattle farming [3].

Other Materials Discharged Into Nature

Water Pollution. This comprises point source water pollution (BOD_5[293], DRP[294], total phosphorus, NH_4, TKN[295] and NO_3) and non-point source water pollution (N and P).[296]

[293] Biochemical oxygen demand (BOD_5) is an indicator of microbial contamination. It measures the amount of oxygen in a water sample that is consumed over a five-day test period by the micro-organisms and biochemical processes that break down rotting organic matter. BOD_5 increases with the amount of dead organic material in water, and indicates the potential for algal growths and depletion of dissolved oxygen.

[294] Dissolved reactive phosphorus (DRP) is likely to cause excessive algal growths in waterways.

[295] Total Kjeldahl nitrogen (TKN) is the sum of organic nitrogen and ammonia in a water body arising typically from sewage and manure discharges.

[296] These figures were derived from private resource consents, and do not include local government sewerage reticulation resource consents. For this reason, pollution in water discharged by industries and households into the sewerage reticulation system is not accounted for here.

Personal and other community services [48] was the highest provider (270 t) of point source water pollution in the Auckland Region (largely TKN and BOD_5) primarily from its waste disposal services. Second and third highest point source water polluters were dairy cattle farming [3] (210 t) and livestock and cropping farming [2] (60 t), mainly from effluent. The agricultural industries are the largest providers of non-point source water pollution from effluent runoff into water systems such as the Pahurehure catchment, with dairy cattle farming [3] accounting for more than half at 4,950 t, and livestock and cropping farming [2] (1,650 t) and other farming [4] (1,630 t) second and third respectively.

Air Emissions. These comprise energy use emissions (CO_2, NO_2, CH_4), non-energy industrial air emissions (CO_2, PM10[297], CO, NOx, SOx, VOC[298]), vegetation/land cover emissions (CH_4, CO, H_2S, N_2O, NMHC[299], NO, NO_2, NOx, VOC) and farm animal emissions (CH_4, NH_3). CO_2 emissions make up 99.9 percent of the energy use emissions and are predominantly the result of high vehicle usage in the Auckland Region. A third of all CO_2 emissions in the Region are associated with households (1.86 million t) for private transport, and the road transport [33] industry (1.15 million t) for road freight, buses and taxis. Basic metal manufacturing [21], mainly Glenbrook Steel Mill, and paper and paper product manufacturing [16], largely Penrose Pulp and Paper Mill, together account for 26.6 percent of total CO_2 emissions in the Region. Similarly, CO_2 emissions make up the bulk (63.9 percent) of non-energy industrial air emissions, with the largest producer being non-metallic mineral product manufacturing [20] at 0.86 million t (or 54.3 percent). Vegetation/land cover emissions produced by the agricultural industries amounted to 0.05 million t, of which 90.9 percent comprised NMHC and VOC emissions. Livestock and cropping farming [2], dairy cattle farming [3] and other farming [4] were responsible for all farm animal emissions of 0.04 million t.

[297] Particulate matter less than 10 microns in diameter (PM10) consisting of tiny solid or liquid particles of soot, dust, smoke, fumes, and aerosols.
[298] Volatile organic compounds (VOC) are organic chemical compounds such as aldehydes, ketones and hydrocarbons that have high enough vapour pressures under normal conditions to significantly vaporise and enter the atmosphere, and participate in atmospheric photochemical reactions.
[299] Non-methane hydrocarbon (NMHC) emissions are biogenic emissions of organic compounds consisting of hydrogen and carbon (excluding methane (CH_4)), which strongly influence the chemical composition of the troposphere through photochemical reactions.

Appendix J

Assessing the Value of Auckland Region's Ecosystem Services

The 'total economic value' (TEV) taxonomy promoted by Pearce *et al.* (1989), Perrings (1995a, 1995b), Costanza *et al.* (1997), Balmford *et al.* (2002) *inter alia* was used to assess the value of Auckland Region's ecosystem services. The TEV of an ecosystem service may be defined as,

$$TEV = DV + IV, \qquad (J.1)$$

where DV and IV respectively denote the direct and indirect use-value[300] of the ecosystem service. DV is the use-value of all goods and services derived from the direct use of the ecosystem service (e.g. food/fibre production, water supply), while IV is the use-value derived from ecosystem services supporting or protecting direct use activities (e.g. climatic regulation, erosion control, nutrient cycling).

J.1 Valuation Approach

The conventional neo-classical valuation approach, based on marginal analysis, was used to assess the direct and indirect use-value of Auckland Region's ecosystem services. This approach has been widely used in valuing environmental assets – refer to Mitchell and Carson (1984) and Kerr and Sharp (1987). Valuation is a matter of how marginal changes in the quality (or quantity) of an ecosystem service impact on human welfare. As the quality of an ecosystem service changes, the marginal costs may be measured by a supply curve, and the marginal benefits by a demand curve. Figure J.1 schematically represents the supply and demand curves for a substitutable ecosystem service. It should be noted however that unlike most market commodities, many ecosystem services are non-substitutable and therefore Costanza *et al.* (1997) suggest that supply and demand curves similar to those of Figure J.2 are more applicable. Notably, for a non-substitutable ecosystem service the demand curve approaches infinity at low levels of an ecosystem service. This is because for most ecosystem services there is a minimum level of non-substitutable service required for human survival. Furthermore, the supply curve for a non-substitutable ecosystem service is near vertical. This indicates that the supply of the ecosystem service cannot readily be varied by human intervention. The TEV

[300] Note the term 'indirect use value' is *not* the same as the 'indirect effects' term used in input-output analysis. 'Indirect use value' refers to the use-value derived from ecosystem services supporting or protecting direct use activities, while 'indirect effects' in input-output analysis refers to the backward linkage or flow-on economic impacts that occur in an economy as a result of economic change in a given industry.

generated by an ecosystem service is the sum of the consumers and producers surplus bounded by the areas a, b, c in Figures J.1 and J.2.

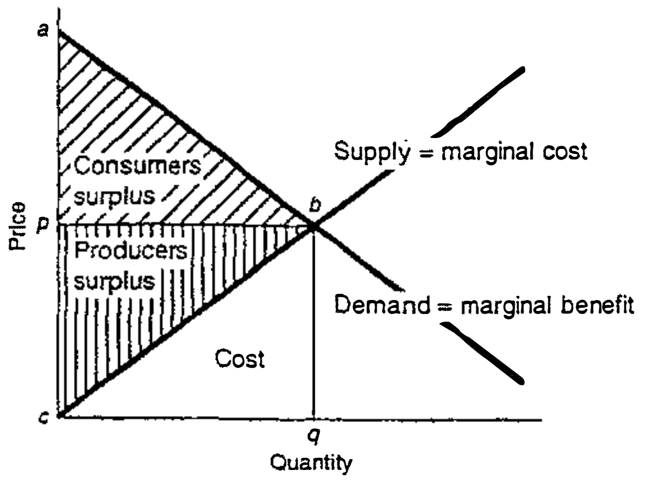


Figure J.1 **Estimation of the Consumers and Producers Surplus for a Substitutable Ecosystem Service**

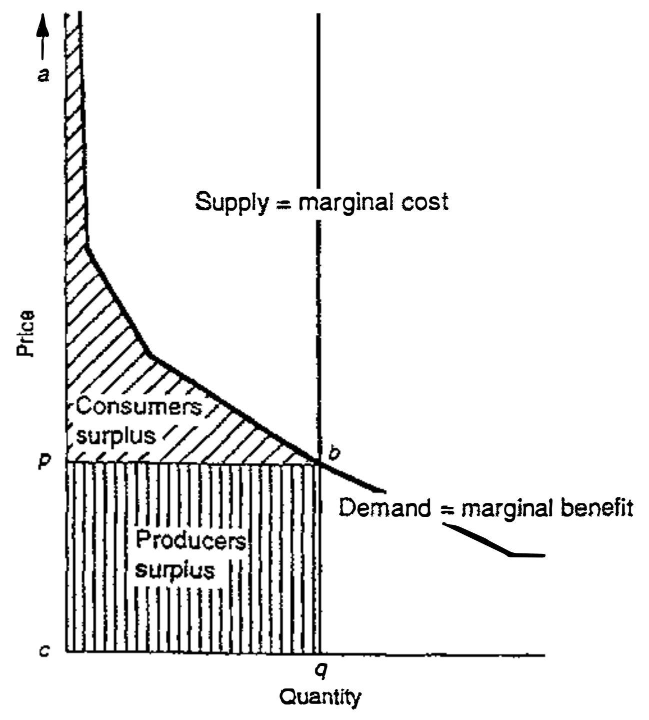


Figure J.2 **Estimation of the Consumers and Producers Surplus for a Non-Substitutable Ecosystem Service**

J.2 Valuation Methods

A substantial portion of the direct use-value of an ecosystem service may be measured using market values as recorded in Statistics New Zealand's System of National Accounts (SNAs).[301] This includes, for example, food, fibre and forestry products. The remaining portion of direct use, and all indirect use, of the ecosystem service are typically non-tradable, and hence have no market value. In these instances non-market valuation techniques such as Hedonic Pricing (HP), Willingness to Pay (WTP), Replacement Cost Method (RCM), and Willingness to Accept Compensation (WTA) may be used to impute a value for an ecosystem service. The virtual absence of suitable New Zealand studies required the use of a wide range of overseas studies to estimate non-market values.

It is beyond the scope of this thesis to discuss the well-known limitations of the neo-classical valuation approach – readers are instead directed to Blamey and Common (1994), Goodstein (1995), Norton (1995) and More *et al.* (1996). Nevertheless, it is important to note that the method is essentially anthropocentric as values are determined by the subjective preferences of human valuers. Significant operational difficulties exist with reliably measuring preferences that are typically predicated on short-term perception and often incomplete knowledge.

J.3 Methodological Sequence

The methodological sequence for deriving the TEV of Auckland Region's ecosystem services is outlined in Figure J.3 and discussed further below.

J.3.1 Auckland Region's Ecosystem Types and Services

In Steps 1 and 2 of the methodological sequence Auckland Region's major ecosystem types were identified and their associated land area quantified in hectares – covering both the terrestrial and marine environments. The Auckland Region landscape was divided into ten core ecosystem types, derived from Terralink Ltd's Land Cover Database (LCDB)[302], that provide value to humans (the original LCDB land use classes are indicated in parentheses).

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[301] It is important to note that the valuations undertaken here only measure ecosystem service appropriation on an annual basis, and are thus *not* a measure of the stock of ecosystem services. The latter would be a very difficult task, fraught with not only operational difficulties, but also theoretical problems (Faucheux and O'Connor, 1998), including how best to aggregate heterogeneous forms of capital – a long standing problem in economics (refer to the so-called 'Cambridge Capital Controversy').

[302] The LCDB is a digital thematic map of mutually exclusive polygons representing sixteen land cover types – generated from mainly satellite imagery acquired between October 1996 and March 1997. Forest Research Ltd has assessed the overall map accuracy at 93.3 percent, with the accuracy of the land cover

Auckland Region's terrestrial ecosystems were divided into the following six types:

- *Agriculture (Primarily high producing pasture).* This is land used for pastoral farming (sheep, beef, dairy, deer *etc.*) and arable cropping (wheat, barley, oat, peas, *etc.*). Pasture is predominantly made up of exotic sward grassland of good quality, reflecting high levels of soil fertility and grazing management. This ecosystem type is the largest in area, accounting for an estimated 273,891 ha or 56.9 percent of the Region's terrestrial area.

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classes ranging from 81.1 percent to 97.1 percent. Scrub was the least accurate land use class due to its small, patchy and dispersed coverage – often smaller than the minimum mapping unit of 1 ha.

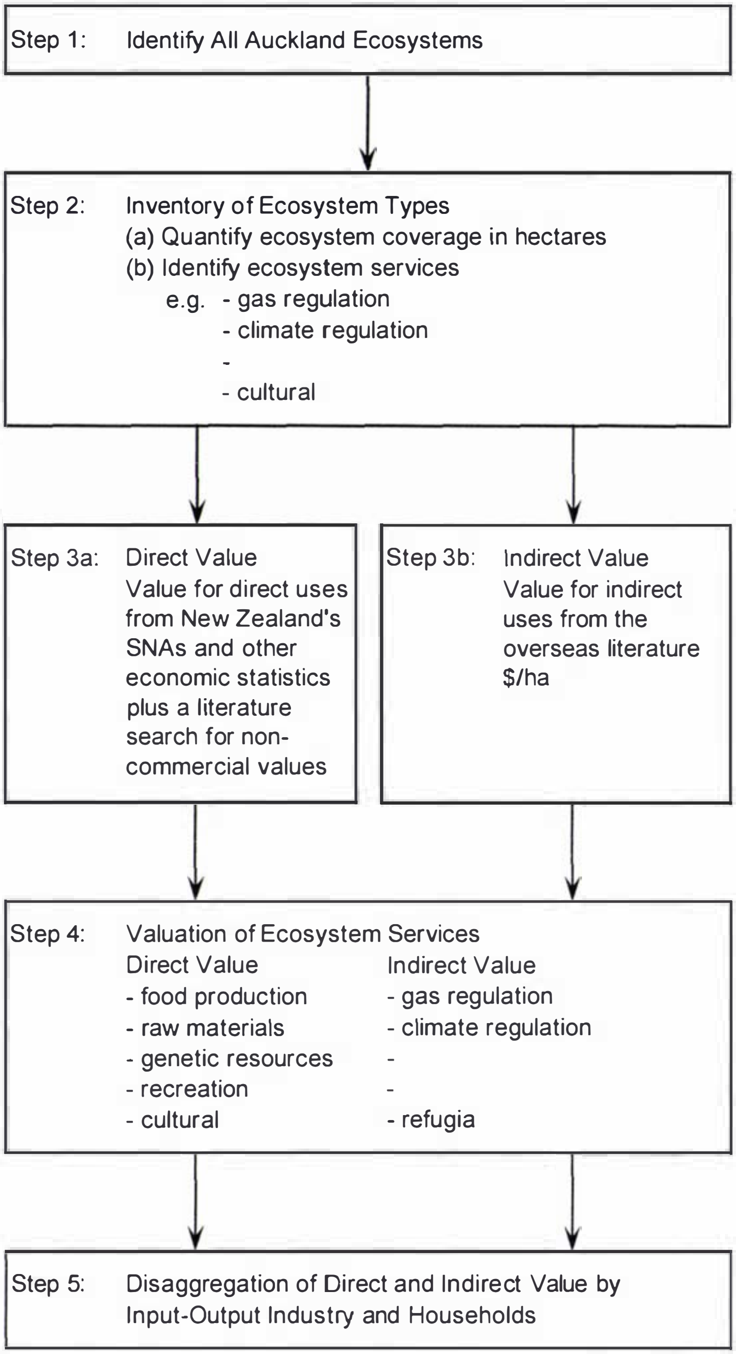

Figure J.3 Methodological Sequence for the Estimation of the Total Economic Value (TEV) of Auckland Region's Ecosystem Services

- *Horticulture (Primarily horticultural)*. This is land primarily used for nurseries, flower-growing, orchards, kiwifruit, vineyards, and market gardens. This represents an admixture of human made and maintained ecosystems of flower-growing, fruits and garden vegetables, with extensive viticulture located in the vicinity of Kumeu and Matakana in Rodney District. This ecosystem type covers an estimated 3,475 ha.
- *Forest (Planted forest, Indigenous forest)*. This refers to both exotic and indigenous forest. Exotic (mainly commercial) plantations cover primarily *Pinus radiata*, located predominantly in Rodney and Franklin Districts and Manukau City. Indigenous forest

includes tall forest canopy species, e.g. podocarp, broadleaf, beech and so on, mainly located in protected Regional Park and State Forest Parks areas such as Waitakere Ranges and Hunua Ranges Regional Parks. This ecosystem covers an estimated 113,196 ha, which amounts to 23.5 percent of the Region's terrestrial area.

- *Scrub (Scrub).* This consists of woody vegetation where shrub/tree cover is less than 20 percent. This is typically made up of Manuka and Kanuka (*Leptospermum* spp), bracken or bracken-like ferns. This ecosystem type is the third largest in area, accounting for 58,184 ha or 12.1 percent of the Region's terrestrial land area, with the largest areas located on Great Barrier, Little Barrier, Kawau and Rangitoto Islands.
- *Urban open space (Urban open space).* This represents land utilised for sports fields, golf courses, parklands, wildlife sanctuaries, reserves, camping grounds, botanical gardens, cemeteries, zoos and the like. Regional parks[303] and reserves make up a significant component of this ecosystem type. Notable urban open spaces include Whenuapai Air Base and Auckland International Airport, as well as areas such as Cornwall Park (171 ha) and Auckland Domain (75 ha), Auckland Regional Botanical Gardens (64 ha) and Western Springs Lakeside Park (60 ha). This ecosystem type is estimated to cover 8,407 ha.
- *Urban Areas (Urban Area).* This includes land bound by the metropolitan urban limits including Auckland, Manukau, Waitakere, and North Shore Cities, and smaller urban areas in the Papakura, Franklin and Rodney Districts. This ecosystem type covers an estimated 33,231 ha, or 6.9 percent of the Region's terrestrial area.
- *Mines.* This represents mines, gravel pits and dump sites. The largest area is found in the vicinity of Glenbrook steel mill in Franklin District, with smaller areas represented by quarries in Papakura District and Rodney District. This ecosystem type is estimated to cover 405 ha.

There are two additional terrestrial land cover types in the LCDB which were not considered in this analysis: (1) bare ground which consists of non-pastoral exposed soil and rock, and (2) beach sands and dunes. The lack of $ per ha estimates was the primary reason why these land cover types were not valued. Together these land use types cover an estimated 2,806 ha, with beach sands and dunes comprising more than 85 percent of this figure.

Auckland Region's aquatic ecosystems were also divided into six classes:

[303] Includes regional parks within the urban area that are not forested such as Auckland Botanical Gardens and Ambury Regional Park.

- *Lakes (Inland water[304]).* Lakes are large natural bodies of standing fresh water. They normally consist of distinct zones that provide a variety of habitats and ecological niches. Notable Auckland Region lakes include Lake Ototoa (162 ha), Lake Pupuke (106 ha), and Lake Pokorua (28 ha). In addition, numerous reservoirs are found in the Hunua and Waitakere Ranges. This ecosystem type also covers an estimated 1,258 ha, including a variety of smaller water holes on farm properties.
- *Rivers (Inland water).* Rivers refer to a natural flow of freshwater along a definite course usually into the sea. Major catchments in the Auckland Region include the Pahurehure, Northern Manukau and Wairoa catchments. This ecosystem type also includes smaller rivers, streams and waterways, and covers an estimated area of 162 ha.
- *Wetlands (Inland wetlands).* This consists of areas that are inundated by freshwater and dominated by herbaceous plant communities. Wetlands are located throughout the region, but concentrations exist in the vicinity of, for example, Kaipara River in Rodney District, and Lakes Wainamu and Waiataru in Waitakere City. Land management practices have reduced or damaged by many of the Region's wetlands. This ecosystem type represents an estimated 114 ha.
- *Estuaries (Coastal wetlands).* This refers to semi-enclosed wetlands that are inundated by salt water, but diluted by fresh water. Estuaries are strongly affected by tidal action, with seawater being mixed with fresh water from land drainage (Knox, 1980). The nutrient rich status of estuaries is well known and is reflected in the high biological productivity of these ecosystems. Auckland Region's estuarine ecosystems are extensive, particularly around Kaipara and Waitemata Harbours, and have been estimated to cover 3,175 ha.
- *Mangroves.* Extensive mangrove swamps are found particularly around the Region's estuaries, with concentrations around Kaipara, Mahurangi and Waitemata Harbours. This ecosystem type covers an estimated 7,450 ha or 1.4 percent of the Region's terrestrial land area.
- *Coastal zone and coastal marine area ecosystem.* Auckland Region's coastal ecosystems extend from the shoreline out to a twelve-mile statutory boundary. This is separated into two main categories: (1) the coastal zone which extends 1km out from the coastline, and (2) the coastal marine area which extends 12 km out excluding the coastal zone. The coastal zone is typically more nutrient rich, biologically productive and richer in biodiversity than the deeper ocean. Northland Region shares the northern

[304] The LCDB does not distinguish between lake and river land cover types. The ecosystem services provided by lakes and rivers are however significantly different. For this reason it was necessary to use Landcare Research's Land Resources Inventory (LRI) as an alternative data source. By corollary, the area covered by the LCDB 'inland water' land cover class may not equate with the LRI figure used in this report.

coastal boundary, and Waikato Region the southern. This area encompasses an estimated 1,125,766 ha, which is equivalent to approximately 233.9 percent of the Region's terrestrial area.

Furthermore, the ecosystem services offered by each ecosystem type were also identified. These are summarised in Table 7.7 of Chapter 7.

J.3.2 Estimates of the Direct Use-Value of Ecosystem Services

Estimation of the direct use-value of Auckland Region's ecosystem services involved steps 3(a) and 4 of the methodological sequence. Ecosystem services that provide direct value include water regulation (e.g. supplying water to industry), food production, raw materials production, recreation and cultural services. Nearly all food production and raw materials production (e.g. wool and wood products) have market values and hence these values can be abstracted from the System of National Accounts (SNAs). Recreation, cultural services and most of the water regulation usually do not have a market value. In these cases literature-based estimates were relied on, particularly worldwide averages from Costanza *et al.* (1997).[305]

J.3.3 Estimates of the Indirect Use-Value of Ecosystem Services

Estimation of the indirect use-value of Auckland Region's ecosystem services was undertaken in steps 3(b) and 4 of the methodological process. Step 3(b) involved matching ecosystem services from Costanza *et al.* (1997) with particular Auckland Region ecosystem types. For example, the ecosystem type agriculture was considered to deliver the same value of ecosystem services as Costanza *et al.*'s (1997) global grass/rangelands ecosystem type. In this way, the indirect values ($ per ha) were considered to be gas regulation ($\$USA_{1994}$ 7/ha), disturbance regulation ($\$USA_{1994}$ 3/ha), and so on. Local differences peculiar to Auckland Region were also accounted for by various adjustments.

[305] The work by Costanza *et al.* (1997) represents a synthesis of more than 100 attempts to value ecosystem services using a range of techniques including hedonic pricing, contingent valuation and replacement cost methods. Balmford *et al.* (2002), in largely an update of the earlier Costanza *et al.* (1997) work, found that many of the original studies relied on were largely unsuitable for assessing the value of global ecosystem services. Nevertheless, the Balmford *et al.* (2002) analysis arrives at many of the same key conclusions as the original paper. The work presented in this thesis was undertaken prior to the publication of the Balmford *et al.* (2002) paper and therefore does not incorporate its findings.

J.3.4 Estimation of the Auckland Region's TEV

Step 4 involved, for a given Auckland Region ecosystem type, multiplying the total hectares (from Step 2) by a vector of ecosystem service values (from Step 3(b)). This multiplication of hectares by $ per ha then facilitated the calculation of some direct value and all indirect value ($). Where necessary the estimates were converted into 1998 New Zealand dollars using exchange rates.[306] Summing the direct and indirect use-value contributions across all ecosystem types and services produced the TEV of the Region.

J.3.5 Distribution of Auckland Region's TEV across 48 Input-Output Industries

In Step 5 Auckland Region's TEV was distributed across 48 input-output industries and households. This required Geographical Information System (GIS) 'cookie cuts' of the LCDB database. First, the LCDB was dissected with Agriculture New Zealand Ltd's Agribase to obtain estimates for the Horticulture and fruit growing [1], Livestock and cropping farming [2], Dairy cattle farming [3], Other farming [4], Forestry and logging [6], and Mining and quarrying [8] industries. Second, the remaining portion of the LCDB was dissected with each Territorial Local Authority's Digital Cadastral Database (DCDB) to separate non-agricultural business land use from residential (household) land use.

J.4 Theoretical and Methodological Issues

There are many data, theoretical and methodological issues associated with applying the TEV approach to Auckland Region – for which further research effort is required. These issues include:

- *Data paucity*. A severe lack of Auckland Region-specific data for estimating indirect use-value. A thorough biophysical characterisation of Auckland Region's ecosystem services would provide a strong starting point for assessing the value of the region's ecosystem services.
- *Scaling*. Various problems exist with translating global figures down to the level of Auckland Region as has been undertaken for much of the indirect value analysis. Local WTP, RCM and WTA survey-based estimates would significantly improve the estimates of indirect use-value.

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[306] Exchange rates do not always reflect the purchasing power of respective currencies and may also be influenced by short run market aberrations.

- *Valuation of the coastal and marine ecosystems.* The valuation of Auckland Region's coastal zone and coastal marine area ecosystems requires substantially more research.
- *Use of marginal analysis.* Marginal analysis does not account for the non-substitutable nature of some ecosystem services. Other approaches such as those advocated by Ulanowicz (1991) and Patterson (1998) may provide more critical insights.
- *Anthropocentrism.* Marginal analysis is by definition anthropocentric, which can easily lead to intrinsic and contributory values being overlooked or underestimated.

J.5 The Auckland Region TEV

The TEV results for Auckland Region's terrestrial ecosystems are summarised below by (1) ecosystem type and (2) ecosystem service. A crude estimate of the use value derived from the Region's coastal, as defined by the legislated 12 nautical mile boundary, ecosystem services is also recorded. Overall, the TEV of Auckland Region's ecosystem services for the study year were valued at $2.32 billion.

J.5.1 By Terrestrial Ecosystem Type

The total direct and indirect use value of terrestrial ecosystem types located within the Auckland Region, as shown in Table J.1, was estimated to be $1.03 billion for the study period. By comparison, Auckland Region's Gross Regional Product (GRP) was estimated to be $33.2 billion for the same period. Direct use value derived from terrestrial and land-based aquatic ecosystems in the Region amounted to $522.53 million, of which an estimated $492.0 million is directly reconcilable with the Auckland Region GRP. Some $98.3 million of the direct use value measured by the SNAs is derived from agricultural ecosystems, largely in the form of food and fibre products. A further $3.2 million is delivered by way of water regulation services. Direct use value not measured by the SNAs includes the bulk of water regulation ($13.0 million) services, along with recreation ($15.3 million) and culture ($2.3 million) services. The indirect use value of terrestrial and land-based aquatic ecosystems was estimated to be $511.4 million. This contribution is entirely omitted from region's GRP estimate. Just under 40.0 percent of the indirect use value was delivered by agricultural ecosystems ($198.0 million), mainly in the form of erosion control ($125.1 million) and waste treatment ($44.4 million).

Overall, the Region's most valuable ecosystem in use terms was agriculture at $299.6 million. This is not surprising given the spatial extent of the agriculture ecosystem in Auckland Region. Lakes were the next most valuable ecosystem at $188.1 million, followed by estuarine at $134.9 million. This reinforces the well-known regional importance of these ecosystems. The remaining ecosystem types (forest, wetlands, scrub, rivers, horticulture, mangrove, mines, urban areas and urban open space) delivered an estimated $411.5 million of services.

Table J.1 Direct and Indirect Use Value Derived from Auckland Region's Terrestrial Ecosystem Types, 1997-98

Ecosystem Type	Direct Use Value Measured by SNAs	Direct Use Value Not Measured by SNAs	Indirect Use Value	Total Direct and Indirect Use Value
	$ million	$ million	$ million	$ million
Agriculture	98.32	3.24	197.99	299.56
Lakes	170.50	10.76	6.83	188.09
Estuarine	0.00	2.40	132.47	134.86
Mines	134.77	0.00	0.00	134.77
Forest	38.11	8.00	65.70	111.81
Scrub	0.00	0.17	33.65	33.82
Urban Areas	8.55	0.37	24.02	32.94
Mangrove	0.00	0.00	29.58	29.58
Rivers	21.66	1.39	1.08	24.12
Horticulture	20.10	0.02	0.39	20.52
Wetlands	0.00	0.48	13.64	14.12
Urban Open Space	0.01	3.68	6.08	9.77
Total	492.02	30.51	511.42	1,033.96

J.5.2 By Terrestrial Ecosystem Service

The direct and indirect use value derived from Auckland Region's terrestrial ecosystems by ecosystem service is displayed in Table J.2. Water supply services (ranked 1st in value terms) highlights the importance of water in the Auckland Region, providing $207.0 million of services in the study year. Water plays a vital role in the irrigation of pasture, purification of aquifers, and industrial and domestic supply of water. These functions are primarily provided by the Region's land-based aquatic ecosystems – namely rivers, lakes, wetlands and estuaries.

Erosion control services (ranked 2nd) in Auckland Region delivered an estimated $183.6 million. This is not surprising given that the region's land is based on soils and soft rock susceptible to erosion, which without careful land management and grazing practices would be highly prone to erosion.[307] Agriculture, forest and scrub ecosystems play a vital role in reducing the amount of soil loss, sedimentation and other adverse effects caused by erosion.

307 This finding was derived by a GIS overlay of Landcare Research Ltd's Land Resources Inventory (LRI) and Ministry for the Environment's Landcover Database (LCDB).

Nutrient cycling (ranked 4th) provided $124.9 million of ecosystem services to the Auckland Region. This is largely a result of the Region's abundance of estuarine and mangrove ecosystem types which assist in the important functions of internal cycling, processing and acquisition of nutrients.

Raw material (ranked 3rd) and food (ranked 5th) production respectively contributed $181.6 million and $117.9 million of ecosystem services in Auckland Region. These ecosystem goods and services are almost entirely provided by commercial forest and agricultural ecosystems. As such they are sold in commercial markets, and therefore standard economic indicators like the Gross Regional Product directly measure their value.

Waste treatment (ranked 6th) provides $84.1 million or 8.1 percent of the total value of ecosystem services in Auckland Region. Waste treatment includes the recovery of mobile nutrients, along with the removal/breakdown of xenic nutrients/compounds such as those found in animal excrement, fertilisers, industrial chemicals/wastes, cowshed effluent and so on. In this way, natural ecosystems are able to store and recycle certain amounts of the Region's human-made wastes through dilution, assimilation and chemical recomposition.

Other significant regional ecosystem services highlighted in this analysis include disturbance regulation ($32.4 million), climate regulation ($28.0 million), water regulation ($16.2 million), recreation ($15.3 million), biological control ($15.2 million), pollination ($14.9 million), and others ($13.0 million). Together these ecosystem services account for 13.1 percent of the Region's ecosystem services.

Table J.2 Direct and Indirect Use Value Derived from Auckland Region's Terrestrial Ecosystems, by Ecosystem Service, 1997-98

Ecosystem Service	Direct Use Value Measured by SNAs	Direct Use Value Not Measured by SNAs	Indirect Use Value	Total Direct and Indirect Use Value
	$ million	$ million	$ million	$ million
Water Supply	189.24	0.00	17.75	206.99
Erosion Control	0.00	0.00	183.35	183.35
Raw Materials	181.65	0.00	0.00	181.65
Nutrient Cycling	0.00	0.00	124.85	124.85
Food Production	117.90	0.02	0.00	117.92
Waste Treatment	0.00	0.00	84.12	84.12
Disturbance Regulation	0.00	0.00	32.37	32.37
Climate Regulation	0.00	0.00	28.13	28.13
Water Regulation	3.23	12.95	0.00	16.18
Recreation	0.00	15.26	0.00	15.26
Biological Control	0.00	0.00	15.17	15.17
Pollination	0.00	0.00	14.86	14.86
Gas Regulation	0.00	0.00	4.17	4.17
Soil Formation	0.00	0.00	3.75	3.75
Refugia	0.00	0.00	2.92	2.92
Cultural	0.00	2.29	0.00	2.29
Total	492.02	30.51	511.42	1,033.96

J.5.3 Coastal Ecosystem Services

Auckland Region's coastal ecosystem comprises two components: (1) the coastal zone which extends 1km out from the shore, and (2) the coastal marine area which extends 12km out excluding the coastal zone. The total economic value of Auckland Region's coastal ecosystem was valued at $1,281.8 million. This value was derived, by downscaling on a per hectare basis, Patterson and Cole's (1999) equivalent figure for New Zealand's Exclusive Economic Zone (EEZ). This is considered an under-estimate of the true value, as it treats the region's coastal margins and ocean environment as being alike. Coastal zones are typically nutrient rich, biologically productive and richer in biodiversity than the deeper ocean.

Appendix K

Environmental Flows of Land and Energy into the Auckland Region Economy

This Appendix describes the methodological process undertaken in calculating the environmental flows of land and energy into the Auckland Region economy in Table K.1, followed by a more detailed analysis of these flows as presented in Table K.2.

Table K.1 Summary of Methodologies Used to Estimate Physical Flows of Land and Energy

Major Category	Item(s)	Data Sources	Industry Coverage[1]	Spatial Coverage[1]	Temporal Coverage[1]	Methodology
Land	Land	McDonald (1999b) McDonald & Patterson (1999) McDonald & MacGregor (2004)	48 industries and households	New Zealand All Regional Councils All Territorial Local Authorities	YE 31 Mar 1995, 1998, 2001, 2004	Refer to McDonald & MacGregor (2004) for full details. Agricultural land estimates - Agri-Quality New Zealand Ltd's Agri-base database (industries 1, 2, 3, 4 & 6). Forest plantation estimates - MAF's Exotic Forest Description. Roading estimates - National Traffic Database. All other estimates - Quotable Value New Zealand property valuation database.
Delivered Energy	Aviation Fuel, Coal, Diesel, Electricity, Fuel Oil, Geothermal, LPG, Natural Gas, Petrol, Wood	EECA (1996, 2004) Patterson (2004) McDonald *et al.* (2004)	48 industries and households	New Zealand All Regional Councils All Territorial Local Authorities (1998, 2001, 2002, 2004 only)	YE 31 Mar 1995, 1998, 2001, 2002, 2004	Refer to McDonald *et al.* (2004) for full details. Uses the same methodology used to generate the EECA (2002) database, but produces estimates for 48 rather than 33 industries.

Notes:

1. The system boundaries of this thesis are limited to: (1) 48 economic industries and households, (2) the area covered by Auckland Region's statistical boundaries, and (3) the YE Mar 1998.

The flows of land and energy inputs into the Auckland Region economy as presented in Table K.2 are broken down by 48 industries and households and, in the case of energy, by fuel type.

Table K.2 Energy and Land Inputs by 48 Industries and Households, 1997-98

Industry	Land	Energy			
		Fossil Fuels excl. Coal	Coal	Electricity	Other
	ha	TJ	TJ	TJ	TJ
1 Horticulture and fruit growing	3,475	142	0	42	0
2 Livestock and cropping farming	174,097 (1)	210	0	19	0
3 Dairy cattle farming	119,429 (2)	213	0	84	0
4 Other farming	39,905 (3)	203	0	14	0
5 Services to agriculture, hunting and trapping	79	76	14	88	0
6 Forestry and logging	39,352 (4)	131	0	0	0
7 Fishing	364	584	0	5	0
8 Mining and quarrying	1,151	70	24	34	0
9 Oil and gas exploration and extraction	614	44	15	22	0
10 Meat and meat product manufacturing	204	151	277	151	0
11 Dairy product manufacturing	143	1,438	1,556 (3)	411	0
12 Other food manufacturing	717	1,916	224	1,101	0
13 Beverage, malt and tobacco manufacturing	118	615	139	499	0
14 Textile and apparel manufacturing	322	773	237	258	0
15 Wood product manufacturing	438	330	79	383	644 (3)
16 Paper and paper product manufacturing	216	2,042	524 (5)	3,177 (3)	10,444 (1)
17 Printing , publishing and recorded media	451	67	4	260	0
18 Petroleum and industrial chemical manufacturing	200	754	61	611	0
19 Rubber, plastic and other chemical product manufacturing	862	1,293	105	1,047	0
20 Non-metallic mineral product manufacturing	442	908	2,571 (2)	426	0
21 Basic metal manufacturing	261	1,815	7,239 (1)	9,130 (2)	0
22 Structural, sheet, and fabricated metal product manufacturing	458	682	24	202	0
23 Transport equipment manufacturing	297	383	13	113	0
24 Machinery and equipment manufacturing	549	858	38	273	0
25 Furniture and other manufacturing	414	337	52	388	407 (4)
26 Electricity generation and supply	147	0	0	0	0
27 Gas supply	5	0	0	0	0
28 Water supply	11,028	0	0	265	0
29 Construction	558	2,906	0	186	0
30 Wholesale trade	672	4,800 (4)	263	1,499 (4)	65 (5)
31 Retail trade	794	4,129 (5)	241	1,352 (5)	57
32 Accommodation, restaurants and bars	1,806	780	10	1,036	46
33 Road transport	1,017	17,057 (1)	32	153	0
34 Water and rail transport	137	2,529	1	4	0
35 Air transport, services to transport and storage	1,622	6,761 (3)	0	448	0
36 Communication services	467	658	0	456	0
37 Finance	58	141	8	381	0
38 Insurance	19	20	1	55	0
39 Services to finance and investment	23	21	1	57	0
40 Real estate	85	155	9	417	0
41 Ownership of owner-occupied dwellings	0	0	0	0	0
42 Business services	829	711	29	688	0
43 Central government administration, defence, public order and saf	2,527	1,186	87	172	0
44 Local government administration services and civil defence	8,535	6	5	123	0
45 Education	2,358	166	293	243	0
46 Health and community services	1,099	396	417	1,080	0
47 Cultural and recreational services	19,424	142	163	91	0
48 Personal and other community services	5,245	333	155	142	3
49 Households	38,359 (5)	17,034 (2)	566 (4)	12,075 (1)	2,271 (2)
Total	481,373	75,964	15,480	39,660	13,936

Notes:
Figures in brackets indicate top five ranking.

Land inputs. Households are the leading non-agricultural land users in the Auckland Region accounting for a total of 38,359 ha. Livestock and cropping farming [2] is the biggest agricultural land use, and also the largest overall, with dairy cattle farming [3] close behind.

Together these two agricultural industries account for 293,526 ha (or 61.0 percent) of total land use in the Auckland Region. The abundance of recreational parks and gardens, and natural reserves in the Region is reflected in the 19,424 ha appropriated by the cultural and recreational services [47] industry.

Energy inputs. Energy inputs cover the following fuel types: fossil fuels excluding coal, coal, electricity and other (black liquor, geothermal and wood). Total energy use (heat equivalents) in the Auckland Region during 1997-98 was 145,039 TJ. A small number of industries was responsible for using most of the energy. The household sector was the largest user of energy at 31,946 TJ (or 22.0 percent), mainly petrol for private motor vehicles (14,225 TJ) and electricity consumption (12,075 TJ). The road transport [33] industry is the heaviest user of fossil fuels excluding coal at 17,057 TJ, and together with households accounts for 44.9 percent of fossil fuel use. Basic metal manufacturing [21], mainly Glenbrook Steel Mill, was the largest user of coal at 7,239 TJ and, after households, of electricity at 9,130 TJ. Paper and paper product manufacturing [16] utilised the largest proportion of other energy at 10,444 TJ (or 74.9 percent), most of which was black liquor. Electricity usage by this industry was also significant at 3,177 TJ.[308] More than half of all energy used in the Region can be attributed to fossil fuels excluding coal, reflecting the high rates of transport use.

[308] Penrose Pulp and Paper Mill claims to be the fifth largest electricity consumer in Auckland Region (Graham, 2004).

Appendix L

System Dynamics Model of Endogenous Growth

This Appendix presents a Vensim® system dynamics influence diagram, Figure L.1, of an alternative growth engine to the one developed in Chapter 11. An operational version, using hypothetical data, is provided in the Appendix L directory of the accompanying CD-ROM. Data paucity, and to a lesser degree time constraints, prohibited development of a full implementation of this growth engine.[309] The engine builds on the work of Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), and Jones (1995, 1998, 2000). The major focus of the engine is on the causal mechanisms underpinning technological progress i.e. how ideas are formulated that lead to the development of new or enhanced technologies. This differs from the growth models developed in Chapter 10, which assume that technological change has no economic basis. Salient features of the model include:

- *Driven by the potential of profits from designs*. The model endogenises technological progress by assuming that the people engaged in prospecting for new ideas (*people discovering new ideas*) are driven to do so by the potential profits they may generate from selling their designs.
- *Generation of new ideas.* The rate at which new ideas are generated depends on (1) the stock of ideas generated to date (*Ideas*), the productivity of the ideas already discovered[310] (*productivity of research*), and whether the ideas are original or simply duplicates[311] (*duplication factor*).
- *Number of people.* In the current version of the model a larger population generates more ideas, and because ideas are non-rivalrous, everyone in the economy benefits. This is arguably optimistic. Skill levels and education of the population, along with other possible restrictions, are not however taken into consideration.

Of particular concern is the omission of natural capital as a critical factor of production. It is envisaged that future versions would overcome this limitation by incorporating:

- *Raw materials and residuals.* Although ideas are the key human factor driving technological change (i.e. positive feedback leading to economic growth), the

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[309] Popp (2005) has recently suggested a novel method for measuring technological change in environmental models using patents.
[310] This includes both knowledge spillovers (i.e. the 'standing on the shoulders of giants' effect) and the possibility that the discovery of new ideas becomes harder over time (i.e. the 'fishing out' effect).
[311] The so-called 'stepping on toes' effect.

transformation of these designs into commodities (including manufactured capital) will always involve materials/energy, and in turn, the generation of residuals. For this reason critical natural capital, in particular non-renewable and renewable resource stocks, would be incorporated within the model.

- *A race between increasing and diminishing returns.* Given that at least some raw materials and energy will be drawn from non-renewable resource stocks, and that some residuals are not easily assimilated by environmental processes, it may be argued that a race will exist between the increasing returns of technological innovation, and the diminishing returns of non-renewable resource stocks.

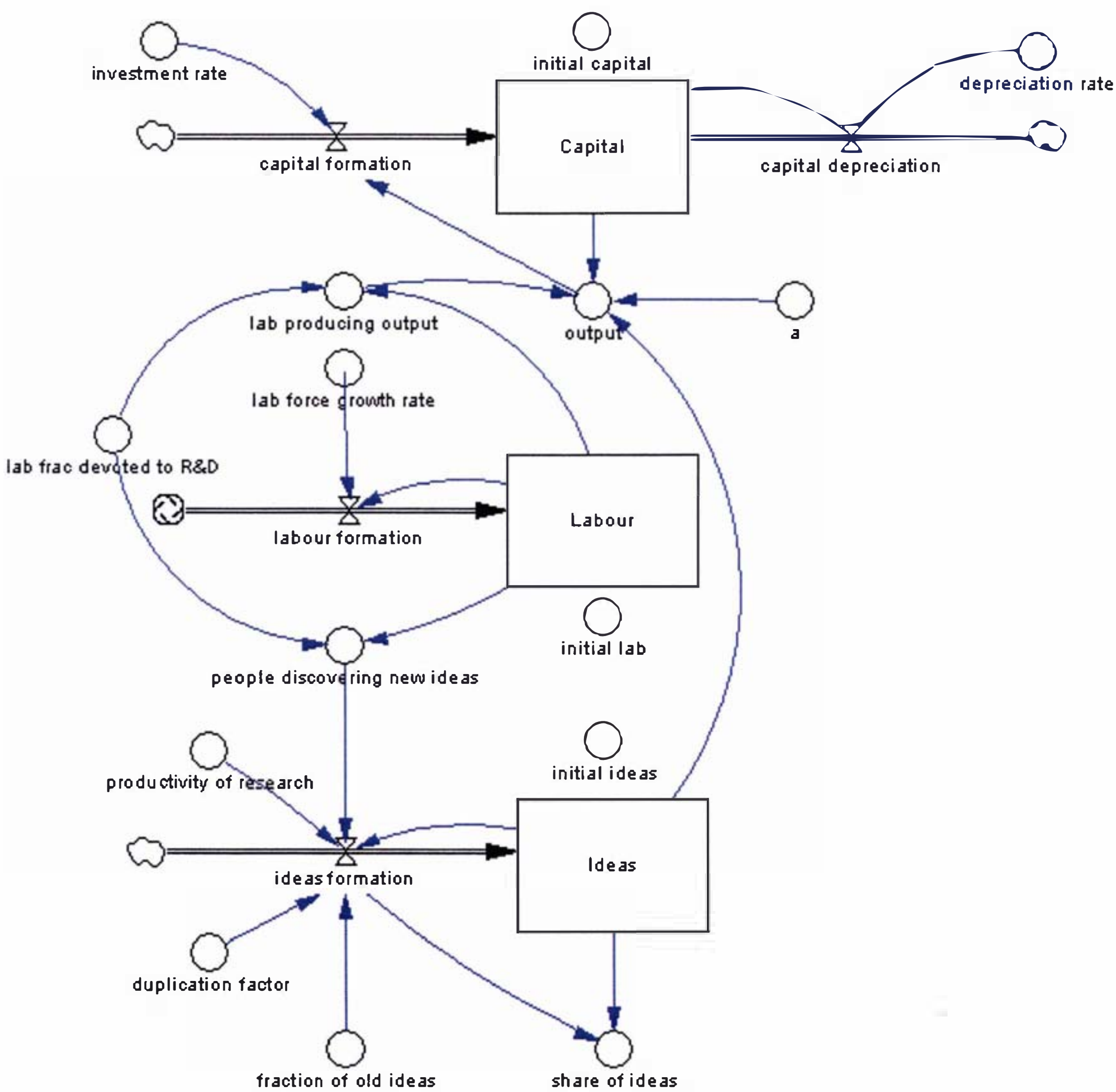

Figure L.1 An Alternative Endogenous Growth Engine

Appendix M

ARDEEM Regression Equations

This Appendix provides details of the time series regression equations used in developing the ARDEEM model. Tables M.1 and M.2 apply to the Population Module; Table M.3 and M.4 apply to the Labour Force Module; Tables M.5, M.6 and M.7 apply to the Growth Module. Table M.7 provides details of the time series regression analysis of the factor elasticities with respect to output used in generating the *output* variable.

Table M.1 ARDEEM Fertility Rate Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
fertility rate $_{10\text{-}14\ yrs,female}$	Linear	y=-0.0058x+0.3873	0.44	1971-2000
fertility rate $_{15\text{-}19\ yrs,female}$	Logarithmic	y=-12.992Ln(x)+71.072	0 88	1971-2000
fertility rate $_{20\text{-}24\ yrs,female}$	Logarithmic	y=-42.204Ln(x)+220.26	0.98	1971-2000
fertility rate $_{25\text{-}29\ yrs,female}$	Logarithmic	y=-20.667Ln(x)+193.69	0.85	1971-2000
fertility rate $_{30\text{-}34\ yrs,female}$	Logarithmic	y=8.575Ln(x)+86.636	0.85	1986-2000
fertility rate $_{35\text{-}39\ yrs,female}$	Logarithmic	y=9.8589Ln(x)+21.826	0.86	1986-2000
fertility rate $_{40\text{-}44\ yrs,female}$	Logarithmic	y=2.0985Ln(x)+2.9	0.75	1986-2000
fertility rate $_{45\text{-}49\ yrs,female}$	Logarithmic	y=-0.1413Ln(x)+0.7685	0.65	1971-2000

Data source: SNZ's INFOS Database DFM-DFASFRNZ, DFM-RASFRNZ, Department of Statistics (1987, 1989), SNZ (1994, 2000a)

Table M.2 ARDEEM Mortality Rate Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
mortality rate $_{0\text{-}4\ yrs,female}$	Logarithmic	y=-0.6856Ln(x)+4.0488	0.87	1971-1995
mortality rate $_{5\text{-}9\ yrs,female}$	Logarithmic	y=-0.0496Ln(x)+0.3662	0.39	1971-1995
mortality rate $_{10\text{-}14\ yrs,female}$	Logarithmic	y=-0.042Ln(x)+0.3293	0.44	1971-1995
mortality rate $_{15\text{-}19\ yrs,female}$	Linear	y=-0.0052+0.6246	0.29	1971-1995
mortality rate $_{20\text{-}24\ yrs,female}$	Linear	y=-0.001x+0.6057	0.01	1971-1995
mortality rate $_{25\text{-}29\ yrs,female}$	Linear	y=-0.0061x+0.667	0.31	1971-1995
mortality rate $_{30\text{-}34\ yrs,female}$	Logarithmic	y=-0.1235Ln(x)+1.0484	0.57	1971-1995
mortality rate $_{35\text{-}39\ yrs,female}$	Logarithmic	y=-0.212Ln(x)+1.6073	0.72	1971-1995
mortality rate $_{40\text{-}44\ yrs,female}$	Linear	y=-0.0448x+2.4444	0.73	1971-1995
mortality rate $_{45\text{-}49\ yrs,female}$	Linear	y=-0.0713x+3.9554	0.79	1971-1995
mortality rate $_{50\text{-}54\ yrs,female}$	Linear	y=-0.0618x+5.5257	0.84	1971-1995
mortality rate $_{55\text{-}59\ yrs,female}$	Linear	y=-0.0992x+8.4472	0.82	1971-1995
mortality rate $_{60\text{-}64\ yrs,female}$	Linear	y=-0.1641x+13.397	0.89	1971-1995
mortality rate $_{65\text{-}69\ yrs,female}$	Linear	y=-0.2574x+20.948	0.82	1971-1995
mortality rate $_{70\text{-}74\ yrs,female}$	Linear	y=-0.4561x+35.018	0.92	1971-1995
mortality rate $_{75\text{-}79\ yrs,female}$	Linear	y=-0.8138x+58.462	0.90	1971-1995
mortality rate $_{80\ yrs\ and\ over,female}$	Logarithmic	y=-21.106Ln(x)+137.35	0.69	1971-1991
mortality rate $_{0\text{-}4\ yrs,male}$	Logarithmic	y=-0.9013Ln(x)+5.2974	0.81	1971-1995
mortality rate $_{5\text{-}9\ yrs,male}$	Logarithmic	y=-0.0904Ln(x)+0.5469	0.60	1971-1995
mortality rate $_{10\text{-}14\ yrs,male}$	Linear	y=-0.0063x+0.4479	0.44	1971-1995
mortality rate $_{15\text{-}19\ yrs,male}$	Linear	y=-0.0147x+1.5998	0.35	1971-1995
mortality rate $_{20\text{-}24\ yrs,male}$	Logarithmic	y=0.0685Ln(x)+1.5949	0.09	1971-1995
mortality rate $_{25\text{-}29\ yrs,male}$	Logarithmic	y=0.0977Ln(x)+1.1865	0.26	1971-1995
mortality rate $_{30\text{-}34\ yrs,male}$	Logarithmic	*y=-0.018Ln(x)+1.412*	*0.02*	1971-1995
mortality rate $_{35\text{-}39\ yrs,male}$	Logarithmic	y=-0.2093Ln(x)+2.2238	0.62	1971-1995
mortality rate $_{40\text{-}44\ yrs,male}$	Linear	y=-0.0552x+3.3643	0.87	1971-1995
mortality rate $_{45\text{-}49\ yrs,male}$	Logarithmic	y=-0.921Ln(x)+6.5626	0.68	1971-1995
mortality rate $_{50\text{-}54\ yrs,male}$	Linear	y=-0.1724x+9.7613	0.93	1971-1995
mortality rate $_{55\text{-}59\ yrs,male}$	Linear	y=-0.2977x+16.508	0.95	1971-1995
mortality rate $_{60\text{-}64\ yrs,male}$	Linear	y=-0.4386x+26.323	0.96	1971-1995
mortality rate $_{65\text{-}69\ yrs,male}$	Linear	y=-0.5866x+40.438	0.95	1971-1995
mortality rate $_{70\text{-}74\ yrs,male}$	Linear	y=-0.871x+63.256	0.94	1971-1995
mortality rate $_{75\text{-}79\ yrs,male}$	Linear	y=-1.093x+95.555	0.88	1971-1995
mortality rate $_{80\ yrs\ and\ over,male}$	Logarithmic	y=-30.346Ln(x)+188.6	0.86	1971-1991

Data source: SNZ's INFOS Database DMM-RASDRSNZ, DMM-RASDRSNZ

Table M.3 ARDEEM Labour Force Participation Rate Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
lab force part rate $_{15\text{-}19,male}$	Logarithmic	y = -0.0644Ln(x) + 0.7266	0.84	1986-2005
lab force part rate $_{20\text{-}24,male}$	Logarithmic	y = -0.0487Ln(x) + 0.9614	0.87	1986-2005
lab force part rate $_{25\text{-}29,male}$	Logarithmic	y = -0.021Ln(x) + 0.9668	0.88	1986-2005
lab force part rate $_{30\text{-}34,male}$	Logarithmic	y = -0.0141Ln(x) + 0.9585	0.66	1986-2005
lab force part rate $_{35\text{-}39,male}$	Logarithmic	y = -0.0152Ln(x) + 0.9682	0.59	1986-2005
lab force part rate $_{40\text{-}44,male}$	Logarithmic	y = -0.0204Ln(x) + 0.9785	0.69	1986-2005
lab force part rate $_{45\text{-}49,male}$	Logarithmic	y = -0.0152Ln(x) + 0.9669	0.80	1986-2005
lab force part rate $_{50\text{-}54,male}$	Logarithmic	y = -0.0142Ln(x) + 0.9382	0.64	1986-2005
lab force part rate $_{55\text{-}59,male}$	Logarithmic	y = -0.0051Ln(x) + 0.8347	0.03	1986-2005
lab force part rate $_{60\text{-}64,male}$	Logarithmic	y = 0.137Ln(x) + 0.3307	0.95	1993-2005
lab force part rate $_{65+,male}$	Logarithmic	y = 0.0261Ln(x) + 0.0713	0.63	1993-2005
lab force part rate $_{15\text{-}19,female}$	Logarithmic	y = -0.0457Ln(x) + 0.6587	0.66	1986-2005
lab force part rate $_{20\text{-}24,female}$	Logarithmic	y = -0.0215Ln(x) + 0.7584	0.37	1986-2005
lab force part rate $_{25\text{-}29,female}$	Logarithmic	y = 0.044Ln(x) + 0.5751	0.73	1986-2005
lab force part rate $_{30\text{-}34,female}$	Logarithmic	y = 0.0229Ln(x) + 0.5985	0.64	1986-2005
lab force part rate $_{35\text{-}39,female}$	Logarithmic	y = 0.0077Ln(x) + 0.6984	0.22	1986-2005
lab force part rate $_{40\text{-}44,female}$	Logarithmic	y = -0.0012Ln(x) + 0.7848	0.00	1986-2005
lab force part rate $_{45\text{-}49,female}$	Logarithmic	y = 0.0373Ln(x) + 0.7105	0.86	1986-2005
lab force part rate $_{50\text{-}54,female}$	Logarithmic	y = 0.0647Ln(x) + 0.5778	0.88	1986-2005
lab force part rate $_{55\text{-}59,female}$	Logarithmic	y = 0.0859Ln(x) + 0.3605	0.66	1986-2005
lab force part rate $_{60\text{-}64,female}$	Logarithmic	y = 0.121Ln(x) + 0.1218	0.87	1993-2005
lab force part rate $_{65+,female}$	Logarithmic	y = 0.0165Ln(x) + 0.015	0.62	1993-2005

Data source: SNZ (2001c, 2005)

Table M.4 ARDEEM Employment by Industry Distribution Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
emp by ind distrib $_{Ind01}$	Linear	y = -0.0033Ln(x) + 0.0329	0.61	1987-2003
emp by ind distrib $_{Ind02}$	Linear	y = -0.0413Ln(x) + 0.2905	0.87	1987-2003
emp by ind distrib $_{Ind03}$	Linear	y = 0.0446Ln(x) + 0.6765	0.89	1987-2003

Data source: SNZ (2003d)

Table M.5 ARDEEM Depreciation Rate Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
depreciation rate $_{Ind01}$	Logarithmic	y = -0.0196Ln(x) + 0.1643	0.54	1972-2003
depreciation rate $_{Ind02}$	Logarithmic	y = 0.0084Ln(x) + 0.0688	0.66	1972-2003
depreciation rate $_{Ind03}$	Linear	y = -0.0001x + 0.0426	0.31	1972-2003

Data source: SNZ's INFOS Database SNC Series.

Table M.6 ARDEEM Investment Rate Regression Equations

Converter	Type of Regression	Regression Equation	R^2	Time Series
investment rate $_{Ind01}$	Logarithmic	y = -0.0093Ln(x) + 0.1077	0.31	1987-2003
investment rate $_{Ind02}$	Logarithmic	y = -0.0022Ln(x) + 0.0575	0.06	1987-2003
investment rate $_{Ind03}$	Linear	y = -0.0002x + 0.115	0.01	1987-2003

Data source: SNZ's INFOS Database SNC Series.

Table M.7 ARDEEM International Exports to Gross Output Regression Equation

Converter	Type of Regression	Regression Equation	R^2	Time Series
intnat exp to go	Logarithmic	y = 0.0137Ln(x) + 0.0789	0.87	1987-2003

Data source: SNZ's INFOS Database SNC Series.

Table M.8 ARDEEM Factors of Production Elasticities with Respect to Output

Converter	Type of Regression	Regression Equation	R^2	Durbin-Watson	Time Series
output $_{Ind01}$	Loglinear	$Y=K^{0.22182}L^{0.14972}M^{0.62846}$	0.92	1.39	1987-2003
output $_{Ind02}$	Loglinear	$Y=K^{0.56862}L^{0.27346}I^{0\ 15792}$	0.81	0.67	1987-2003
output $_{Ind03}$	Loglinear	$Y=K^{0.19354}L^{0.15338}M^{0.65308}$	1.00	1.00	1987-2003

Data source: SNZ's INFOS Database SNC Series, SNZ (2003d). Note: Y denotes output, K denotes capital, L denotes labour, I denotes imports, and M denotes intermediate demand/use.

Appendix N

CD-ROM Software

Please find enclosed in the inside back cover of this Thesis.