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Sustainability and the Global Biogeochemical Cycles: Integrated modelling of coupled economic and environmental systems

A thesis presented in partial fulfilment of the requirements for the degree of

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In

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Abstract

The global biogeochemical cycles (GBCs), which include cycles of C, N, P, S, Cl, I, and H_2O, are extremely important biosphere functions, critical to the maintenance of conditions necessary for all life. Importantly, perturbation of these GBCs has the potential to affect the structure and functioning of the Earth system as a whole. While biogeochemistry research to date has largely focused on 'natural' processes, human economic activities are increasingly recognised as integral components of the GBCs. This thesis draws on both static and dynamic-system modelling approaches to describe the coupled economic and GBC systems, and to develop tools to assist in learning about these systems, with the aim of progressing towards sustainability. First, by drawing on the theoretical frameworks of Input-Output Analysis and Material Flow Analysis, an extensive and coherent static system model of the global C, N, P and S cycles is presented. Data within that static model are then used to calculate a set of sustainability indicators, based on a new and novel concept of 'ecotime'. Essentially, these indicators describe the level at which the global economy, through its transformation of useful resources (i.e. raw materials) into residuals (i.e. wastes, pollutants, emission), appropriates biogeochemical processes. Changes in these and other indicators, under possible future scenarios, are also able to be investigated by a new dynamic model known as 'Ecocycle'. Ecocycle constitutes one of very few attempts to develop an integrated model of the Earth system, explicitly capturing relationships between the GBCs and human activities. A notable feature of Ecocycle is that it represents the general equilibrium-seeking behaviour of an economy within a System Dynamics modelling approach, rather than through an optimisation approach as typically employed. A further significant methodological contribution of the thesis is the development of a technique for translating IO-based accounts between alternative process-by-commodity, commodity-by-commodity, and process-by-process frameworks. This method is required for both the static and dynamic components of the thesis.

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List of Abbreviations

Acronyms

Acronym	Name
AR4	IPCC Fourth Assessment Report
BOD	Biological Oxygen Demand
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
COD	Chemical Oxygen Demand
CTA	Commodity Technology Assumption
DGBCM	Dynamic Global Biogeochemical Cycling Model
DGES	Dynamic General Equilibrium Seeking
DIC	Dissolved Inorganic Carbon
DOC	Degradable Organic Carbon
EDGAR	Emission Database for Global Atmospheric Research
EF	Ecological Footprint
ESAM	Environmentally-Extended Social Accounting Matrix
FAO	Food and Agricultural Organisation
FCS	Fixed Commodity Sales Structure
FIS	Fixed Industry Sales Structure
GHG	Greenhouse Gases
GTAP	Global Trade Analysis Project
GUMBO	Global Unified Metamodel of the Biosphere
IMAGE	Integrated Modelling of Global Environmental Change
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
ISW	Industrial Solid Waste
ITA	Industry Technology Assumption
MA	Millenium Ecosystem Assessment
MFA	Materials Flow Analysis
NPP	Net Primary Production
PIOT	Physical Input-Output Table
SAM	Social Accounting Matrix
SIOT	Symmetric Input-Output Table
SUT	Supply-Use Table
TAR	IPCC Third Assessment Report
VOCs	Volatile Organic Compounds

Chemical Formula

Formula	Name
C	Carbon
$CaCO_3$	Calcium carbonate
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CS_2	Carbon disulphide
DMS	Dimethyl sulphide $(CH_3)2_S$
H_2CO_3	Carbonic acid
H_2S	Hydrogen disulphide
HCO_3^-	Bicarbonate
HNO_3	Nitric acid
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
OCS	Carbonyl sulphide
P	Phosphorus
PO_4^{3-}	Phosphate
S	Sulphur
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate

SI Units

Symbols	Prefixes	Multiples
Z	Zetta	$1\,000\,000\,000\,000\,000\,000\,000 = 10^{21}$
E	Exa	$1\,000\,000\,000\,000\,000\,000 = 10^{18}$
P	Peta	$1\,000\,000\,000\,000\,000 = 10^{15}$
T	Tera	$1\,000\,000\,000\,000 = 10^{12}$
G	Giga	$1\,000\,000\,000 = 10^{9}$
M	Mega	$1\,000\,000 = 10^{6}$
k	kilo	$1\,000 = 10^{3}$

Chapter 1

Introduction

1.1 Sustainability and the Earth's Biogeochemical Cycles

This thesis is concerned with the evaluation of the Earth's biogeochemical cycles, both current and future, from a sustainability economics perspective. Sustainability economics is ethically founded on the normative objective of justice, including justice between humans of present and future generations, as well as toward Nature, within the context of human–nature relationships over the long-term and inherently uncertain future (Baumgärtner and Quaas, 2010a, 2010b).

The global cycling of carbon (C), nitrogen (N), phosphorus (P), sulphur (S), potassium, chlorine, iodine, and other elements, are recognised as extremely important processes provided by the biosphere.[1] Not least of all, these biogeochemical cycles are essential to maintaining and regulating the conditions for life – including human life. This is due to their continual supply of scarce elements needed for biotic metabolism, their role in stabilising temperature, humidity, salinity, acidity, and other environmental conditions, and their ability to convert toxic waste products from one form of life into nutrients for another (Ayres, 1993; Smil, 2002). The biogeochemical cycles are also fundamental to the provisioning of a wide range of other ecosystem services, including food and raw material production and the provision of aesthetic, recreational, and spiritual values (Millennium Ecosystem Assessment, 2003).

The very term 'biogeochemical cycle' implies consideration of a system comprised of *natural* biological and geological processes. Indeed, much of the research to date on biogeochemistry has focused on the natural components of the cycles; for the most part omitting the processes contained within human systems and, importantly, the relationships occurring between natural and human systems. However, increasing recognition of biogeochemical-related environmental problems, including global climate change, widespread acidification of soils and waters, and eutrophication of aquatic and terrestrial ecosystems, has highlighted the significance of human activities within these cycles. It is now recognised that humans are

[1] The biosphere refers to the part of the Earth's surface and atmosphere inhabited by living organisms. Within this thesis, the term biosphere is extended to include the lithosphere due to its role in supporting life. Others have referred to this as the 'geobiosphere'.

increasingly influencing and appropriating[2] the biogeochemical cycles at a global scale (Catton, 1982; Vitousek *et al*., 1986, 1997; Rojstaczer *et al*., 2001; Denman *et al*., 2007; Haberl *et al*., 2007; Venetoulis and Talberth, 2008; Filippelli, 2008; Canfield *et al*., 2010). Van der Voet *et al*. (2000) thus prefer to use the term 'anthropo-biogeochemical' cycles rather than simply 'biogeochemical' cycles.

Human perturbation of the biogeochemical cycles threatens the ongoing provisioning of essential ecological services to future generations. Many authors have conceptualised these material cycles as a sequence of transformation processes and reservoirs that can be represented schematically as stocks linked by flows. As stated by Ayres (1993, p.203), the condition for stability in these cycles "is easily stated: the stocks in each compartment, or reservoir, must remain constant (at least on average); and, for this condition to be met the inflows into each compartment must be balanced exactly (on average) by outflows." If, however, the condition is not satisfied, we must infer that the stock in some compartment(s) is accumulating at the expense of another compartment(s). While we may be assured that the Earth's biogeochemical cycles contain multiple 'negative feedback' structures that enable the systems to regulate following perturbation, the threat is that we may eventually reach a point where self-regulating feedbacks are insufficient to maintain the system within a desirable state for humans. The necessity of constraining the scale of economic activity relative to the regenerative capacity of the biogeochemical cycles thus has normative weight, both now and into the future, because it is a prerequisite to the achievement of distributive justice and, hence, sustainability.

1.2 The Need for an Integrated and System-Based Approach

Analysis of the Earth's biogeochemical cycles from the perspective of sustainability economics requires an integrated and system-based approach. Economics, as the science of resource allocation, is certainly important. However, as is becoming increasingly recognised, the biophysical and economic systems are integrated complex systems characterised by interdependencies, nonlinearities, time-delayed feedback loops, emergent phenomena, and chaotic behaviour (Kauffman, 1993; Patten and Jørgensen, 1995). As noted by many authors to date (e.g. Costanza *et al*. (2007b), Baumgärtner *et al*. (2008) and Komiyama *et al*. (2011)),

[2] In this context, 'appropriation' denotes taking-up or capturing of functions performed by biogeochemical processes (e.g. primary production, matter decomposition, soil formation) to serve human purposes.

these complexities pose significant challenges that are impossible to address from within the confines of any one discipline. Clearly an approach is required that incorporates salient theories, tools, and knowledge sets of the natural and social sciences.

This thesis adopts a complex systems science approach as the framework for integration. Inquiry into the concept and nature of systems, which in the most general sense can be defined as "a set of interrelated elements" (Ackoff, 1971, p.661),[3] started to gain momentum from around the 1930s, reflecting a growing dissatisfaction with the reductionist approach of mainstream science (von Bertalanffy, 1972). Over time systems approaches, including those concerned with *complex adaptive systems* have led to the development of a variety of terms to help describe the characteristics and behaviour of systems, as well as a variety of modelling methods. A reoccurring theme within the literature is the limited ability to predict behaviour of complex systems, including biological, ecological and human systems. Many persons involved in system analysis advocate that the purpose of system enquiry and modelling is not to attempt to predict the behaviour of systems, but rather to foster understanding of systems, particularly the processes, interactions, and feedback mechanisms within systems that generate changes in dynamics and structure (e.g. Phillips (1969), Kurtz and Snowden (2003) and Meadows and Robinson (2007)).

Not only does the topic of this thesis require an *inter*disciplinary approach, it is also necessitates *trans*disciplinary science. The distinction invoked here is that while interdisciplinary refers to some kind of cooperation between or bringing together of scientific disciplines, transdisciplinarity involves an actual interrelationship between science and society (Baumgärtner *et al*., 2008).[4] A key facet of transdisciplinary science is the need to deal with values and normative judgements so that sustainability is substantiated across real environments and societies (Hirsch Hadorn *et al*., 2006; Pohl, 2008; Lang *et al*., 2012). This means that from the outset it is necessary to specify what it is that is sought to be achieved by the 'umbrella aim' of sustainability, to what extent, and ultimately, for what reasons (Baumgärtner *et al*., 2008).

[3] Meadows (2008, p.188) systems definition "a set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviours" is perhaps even more useful.

[4] Refer also to Functowicz and Ravetz (1993) and Norgaard (1989) on the related concepts of 'post normal science' and methodological pluralism.

1.3 Research Aims and Objectives

1.3.1 Overall Aim

The primary aim of this thesis is to develop and apply an integrated systems modelling framework of coupled economic and global biogeochemical cycling systems to progress sustainability. Figure 1.1 illustrates the way in which the key research objectives identified below relate to and contribute towards this overall research aim. Note that the ovals/circles describe key outcomes that not only link the research objectives to the research aim, but also link the individual research objectives together.

1.3.2 Specific Objectives

Specific objectives for this thesis are to:

(1) provide a theoretical interpretation of the concept of sustainability, uniquely focused on the topic of biogeochemical cycling. In turn, presenting a set of core sustainability principles that guide the development, use, and interpretation of the systems models and indicators developed in this thesis.

(2) undertake a descriptive and functional analysis of the Earth's biogeochemical cycles, focusing on the so-called 'grand nutrient cycles' of C, N, P and S. This analysis will enable us to understand the current state of these cycles, including answering questions such as: 'What do current material flows and their transformations look like?', 'How do human activities influence these cycles?', and 'Which human activities are responsible for the greatest impacts?'

(3) develop a suite of indicators that enables us to assess progress towards the goal of sustainability in relation to the Earth's biogeochemical cycles. Ideally, these indicators will have a wide scope, allow trends to be determined, and have pedagogic value.

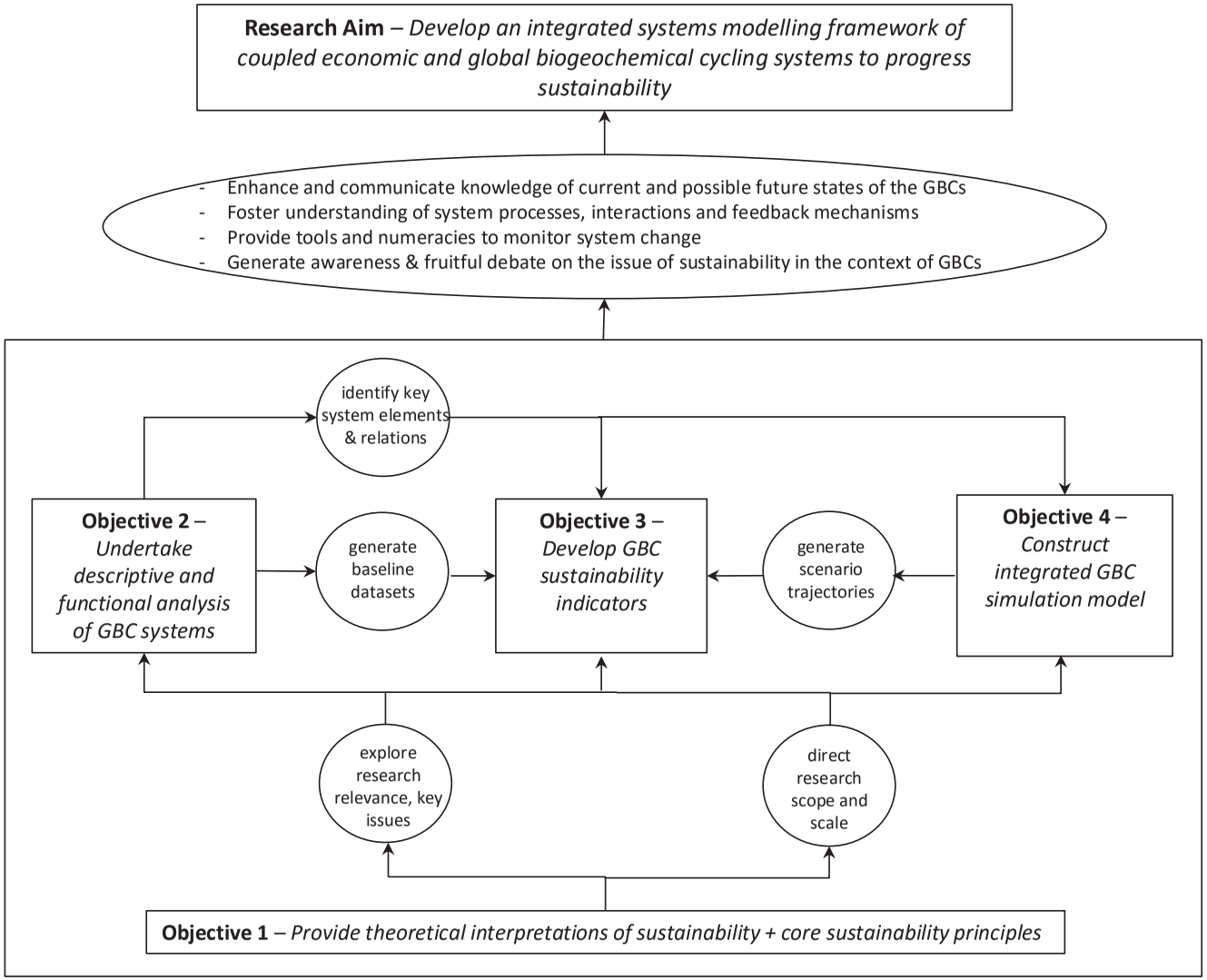

Figure 1.1 **Key Relationships between Research Aim and Research Objectives**

(4) construct an integrated dynamic global simulation model of the Earth's biogeochemical cycles, incorporating both the environment and economy and their interdependencies. This dynamic model will provide a synthesis of the information obtained and analysis undertaken of the biogeochemical cycles, in a way that can be easily communicated to the wider community. This will include functionality for testing what might happen under alternative future global development scenarios.

1.4 Model Scale

Model building, whether undertaken in the formal and structured approach of computer programming or in a less formal manner,[5] is an essential prerequisite for building comprehension of and consensus around major socio-economic and environmental problems. Global biogeochemical cycles are very complex systems operating over a variety of spatial scales. Much of the research that has been, or is currently being, undertaken on biogeochemical cycles focuses on individual ecosystems. Although this research is certainly of great value, it can be difficult to grasp the extent to which outcomes and behaviours captured at the level of individual ecosystems, may ultimately constrain the opportunities available to future generations. The systems models developed within this thesis are deliberately global in nature, with relatively coarse spatial granularity. At this scale, all resources and habitable environments available to humans are captured, and we can most easily evaluate the magnitude or scale of human activities in relation to the biogeochemical cycles for the planet as a whole. With the exception of the climate change research, which mainly focuses on C cycling, there have been relatively few attempts to synthesis this information into a coherent account of the global system. As eloquently stated by Boumans *et al*. (2002, p.529), "[c]ollectively, global models constitute a relatively well focused and coherent discussion about our collective future."

The environmental components of the model are based on relatively coarse global 'commodity stocks' existing within four different spheres – the atmosphere, terrestrial biosphere, oceans, and the lithosphere. By limiting spatial resolution, it is typically possible to build models that are broader, simpler and more transparent; thus better suited for scoping the nature and extent of problems, testing theories and building consensus. The significant resources typically

[5] As has been explained earlier by various systems thinkers, people build mental models to understand systems and inform decisions. Even language itself is an expression of mental modelling, involving the abstraction of systems into simpler forms to enable communication of concepts.

required, both to construct and run high spatial models, are also a valid consideration. This is not to say that there are not significant advantages to undertaking modelling at fine spatial scales, depending on the purpose of the analysis, for example at the level of individual biomes for environmental systems or for individual nations in the case of economic systems.[6] A number of limitations associated with the selected resolution of analysis are discussed through this thesis as appropriate.

1.5 Model Scope

This thesis focuses specifically on the biogeochemical cycles of C, N, P and S. It is recognised that there are other important biogeochemical cycles also worthy of the types of analyses undertaken in this thesis. Water, for example, is an essential compound for life, a key transporter of materials and is a common reactant and product of many biogeochemical processes. Nevertheless, the presence of data, time and financial constraints necessitated some confinement of the scope of the thesis. Even the inclusion of the four cycles considered was an ambitious task for one person to undertake.

1.6 Methodological Approach

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

(1) *Critical reviews and synthesis of the relevant literature related to sustainability in the context of the Earth's biogeochemical cycles*. This includes a review of the normative foundations of sustainability, as well as various economic, thermodynamic, ecological and systems perspectives. The purpose of this literature review and synthesis is to provide a firm theoretical basis for the systems modelling and related indicator development undertaken within the remainder of the thesis.

(2) *Development of a global static system model of the 'within-environment' and 'between environment and economy' biogeochemical flows.* The modelling framework employed systematically accounts for the flow of biogeochemical commodities through biophysical processes, in an analogous manner to the tracing of commodity

[6] A number of multi-national datasets are employed in this thesis to help define or estimate biogeochemical flows caused by economic activities (e.g. GTAP, EDGAR, NAMEA, the FAO Food and Agricultural Commoditeis Production and ForestSTAT databases, and so on). This means that with more resources available, at least some of the system flows could be defined at a finer spatial scale.

production chains within economies. In this way the static system model extends previous Input-Output (IO) based approaches, in particular environmentally extended IO analysis, to create a rich picture of 'within economy', 'within environment' and 'across environment-economy' biogeochemical interactions. The static system model furthermore employs concepts and terminology from Material Flow Analysis to enable easy sharing and application of the databases created among practitioners, and to assist future development (e.g. spatial and temporal disaggregation).

(3) *Development of sustainability indicators.* A method is devised for deriving a suite of indicators describing the level at which the global economy, through its transformation of useful resources (i.e. raw materials) into residuals (i.e. wastes, pollutants, emissions), is appropriating biogeochemical processes. Similar to the development of the static system accounts, the indicators are based on tools and approaches utilised within IO analysis. Specifically, the indicators draw on both the demand-side (Leontief) and supply-side (Ghosh) IO models, populated with data from the static system model of the global C, N, P and S cycles. Importantly the way in which these IO models are applied, which includes incorporation of a time dimension, is both new and novel.

(4) *Construction of a dynamic simulation model*. While the static models help us learn about the behaviour of a system at rest, dynamic models are required to help us think about how a system changes over time. The dynamic model constructed in this thesis is built over a series of steps, with each step involving increasing complexity. Both economic and environmental sub-models are constructed using the tools and techniques of Systems Dynamics. These are then connected to form a single, interconnected, simulation model of the Earth's biogeochemical cycles. The model's behaviour is demonstrated through application of scenarios, enabling us to begin to understand the dynamic tendencies of the system, and identify the direction for further model improvements.

1.7 Thesis Organisation

The thesis is comprised of three interconnected Parts.

Part I	Theoretical Framework
Part II	Static Analysis
Part III	Dynamic Analysis

Note that a number of appendices are also included within the thesis. Of particular importance is Appendix B 'Estimation of Symmetric Input-Output Tables'. The interrelationships between these different parts of the thesis, and the constituent chapters, are set out in Figure 1.2.

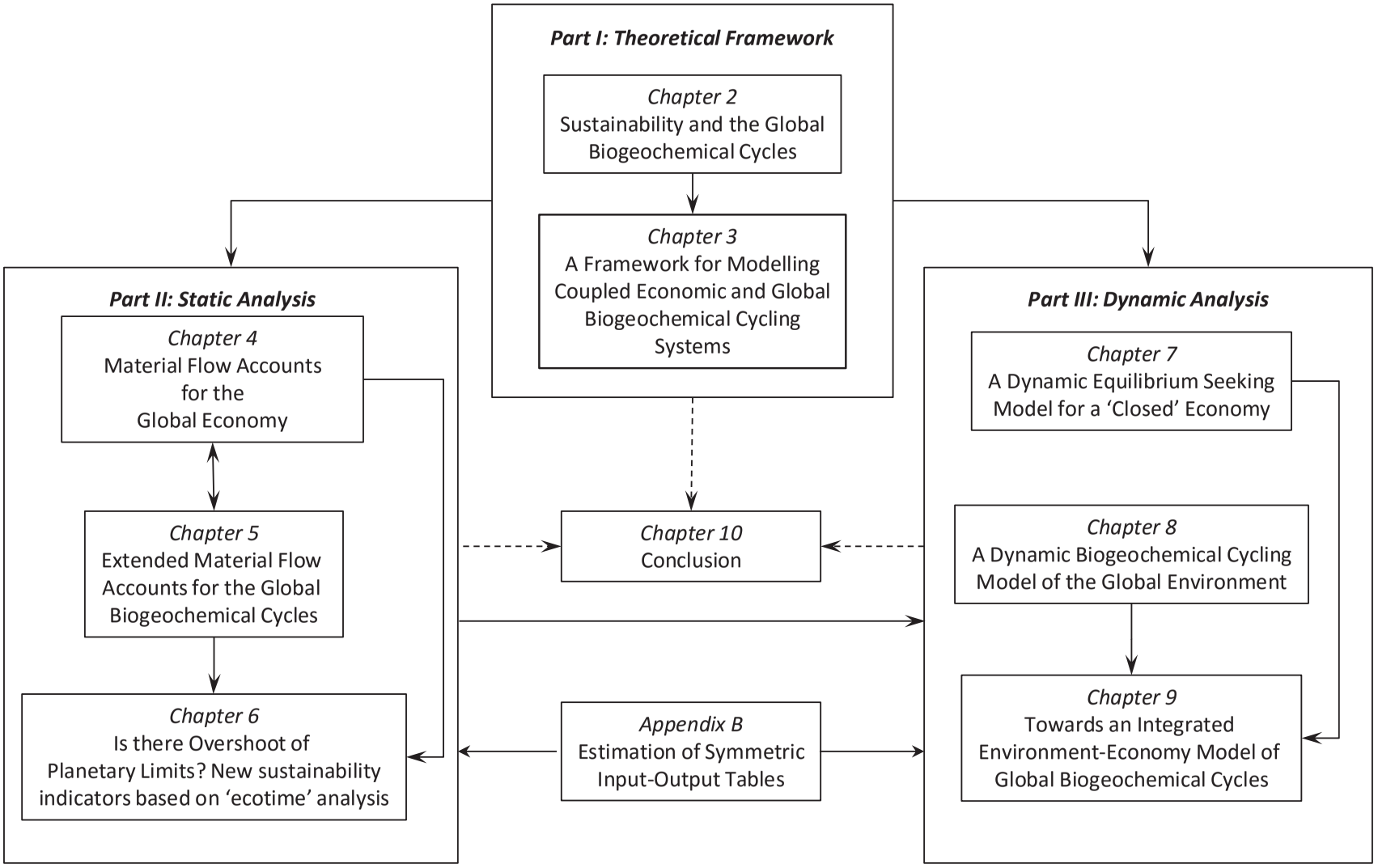

Figure 1.2 Interrelationships between the Different Parts of the Thesis and Constituent Chapters

Part I: Theoretical Framework

In Chapter 2, a literature review of the sustainability concept is provided, focused on the context of biogeochemical cycling. It is acknowledged that the sustainability concept is applied in a vast number of disciplinary fields that, in turn, produce a plethora of sustainability definitions. This chapter discusses particularly the economic, thermodynamic, ecological, and system interpretations of the sustainability concept. An interdisciplinary and transdisciplinary perspective is necessary to address many of the social, economic and environmental issues we face. A keystone of this perspective is the role played by the Earth's biogeochemical cycles in sustaining life. With reference to the biogeochemical cycles, this chapter ends by defining a set of guiding principles for sustainability. In Chapter 3, based on IO analysis, Material Flow Analysis (MFA), and informed by Chapter 2 principles, a clear and comprehensive theoretical framework is presented for conceptualising and describing both the current and possible future state of biogeochemical cycles. This framework includes a definition of system boundaries, exogenous inputs and outputs, and key endogenous stocks, flows, and interrelationships. The framework, which is employed throughout the remainder of the thesis, also accounts for environment, economy, and environment-economy biogeochemical exchanges that occur within the Earth system.

Part II: Static Analysis

In Chapters 4 and 5 a comprehensive static database covering all major C, N, P and S biogeochemical processes for the 2004 year is established. This database is based on an extensive literature review of well over 300 publications. First, Chapter 4 traces the connections *between* the economic and environmental components of the biogeochemical cycles. These element mass flows essentially result from the use of raw materials, and production of residuals (i.e. wastes, pollutants, emissions), by human activities. Note that the Chapter 4 accounts are ordered and described according to the concepts and definitions of Materials Flow Analysis, and therefore can be viewed as a set of material flow accounts for the global economy. Chapter 5 augments Chapter 4, by adding to the database the components of the biogeochemical cycles occurring *within* the environmental system. Due to the need to triangulate data sources in the construction of the database across both environmental and economic processes, Chapters 4 and 5 are highly interconnected. In addition to the summary diagrams presented in these chapters, a number of indicators could potentially be construed to assist in summarising and communicating the information collected. Assisted by a methodology described in Appendix B, Chapter 6 brings together the data described in Chapters 4 and 5 to create a novel suite of static sustainability indicators through which we can

communicate and monitor humanity's dependence on the biogeochemical cycles. Significant insight is gained by comparing the rate of human appropriation of biogeochemical cycling with that of the biosphere's regenerative capacity. In order to calculate these indicators, a new concept of 'ecotime' is defined as the average biogeochemical cycling time available for matter held within different environmental stocks (e.g. CO_2, plants, fossil fuels) to reach biogeochemical processes. It is worth noting that Chapter 6 is published in the journal *Ecological Economics*.[7]

Part III: Dynamic Analysis

In Chapters 7, 8 and 9 a set of dynamic simulation models is created to consider the possible future implications associated with anthropogenic perturbation of the biogeochemical cycles. Chapter 7 develops a Systems Dynamics model of the global economy using a novel dynamic general equilibrium seeking approach. It addresses several inadequacies of standard Computable General Equilibrium (CGE) models including lack of transparency, difficulties in integrating to other models, and omission of transitional and out-of-equilibrium dynamics. Chapter 8 develops a Systems Dynamics model of the global C, N, P and S biogeochemical cycles, drawing on the datasets presented in Chapters 4 and 5. It extends the earlier work of McDonald (2005) by refining the biogeochemical processes, stocks, and flows and their values, but also by calculating future flows using n-order, rather than 1^{st} order equations. A key feature of this chapter is the adoption of an integrated systems perspective emphasising the interconnectedness between the element cycles. Finally, Chapter 9 develops an integrated environment-economy model, known as Ecocycle, by combining the models developed in Chapters 7 and 8. Two trial simulations are undertaken to demonstrate the potential of Ecocycle in helping us understand the possible implications of human activities with respect to the global biogeochemical cycles.

Conclusion

Chapter 10, the concluding chapter, identifies major theoretical/conceptual, methodological, and empirical contributions of the thesis, its key limitations and weakness, and potential avenues for further research.

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[7] Reprinted from *Ecological Economics*, vol. 104, Smith, N.J., McDonald, G.W. and Patterson, M.G., 'Is there overshoot of planetary limits? New indicators of human appropriation of the global biogeochemical cycles relative to their regenerative capacity based on 'ecotime' analysis', pp.80-92, 2014, with permission from Elsevier. The journal article also includes supporting excerpts from Chapters 2–5.

Appendices

Eight appendices are further included to support the thesis. These appendices provide additional background information, supporting methodologies, summaries of data and results, and detailed mathematical equations. Of particular importance is Appendix B, which provides a methodology, based on non-linear optimisation, for constructing Symmetric Input-Output Tables (SIOTs) under various technology assumptions from rectangular Supply-Use Tables (SUTs). SIOTs are employed in Chapters 6, 7 and 9 of the thesis. Although included as an Appendix, it is worth noting that Appendix B is published in the journal *Economic Systems Research*,[8] and is a very important methodological contribution made by this thesis.

[8] Reprinted from *Economic Systems Research*, vol. 23, Smith, N.J. and McDonald, G.W., 'Estimation of Symmetric Input-Output Tables: An Extension to Bohlin and Widell', pp.49-72, 2011, with permission from Taylor & Francis.

Part I Literature Review and Conceptual Framework

"What is the use of a house if you don't have a tolerable planet to put it on?"

Henry David Thoreau, Familiar Letters, 1894

Chapter 2

Sustainability and the Global Biogeochemical Cycles

2.1 Introduction

It has become almost routine for any introductory text on the topic of sustainability to begin by referencing the Brundtland definition:

> *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their needs"* (World Commission on Environment and Development, 1987).

Many commentators have, however, stated that the Brundtland report, especially when read as a whole, was not an attempt to define the notion of 'sustainability' itself, but rather to lay out the aspirations for a particular type of economic growth (Jones, 2011). While acknowledging that the term 'development' is not synonymous with 'growth' Daly (1990), for example, determines that insofar as the Brundtland report emphasises growth in the world economy by a factor of 5 or 10, it is clearly a document more about 'sustainable growth'. He then concludes that because the human economy is a subsystem of a finite global ecosystem, and thus cannot sustain economic growth over long periods, the term sustainable growth should be rejected as a "bad oxymoron" (Daly, 1990, p.402). In light of these criticisms, it is perhaps not surprising that 'sustainability' rather than 'sustainable development' has come to be the more commonly used phrase in academia when referring to issues about humanity's ability to live within environmental constraints. Likewise, the term sustainability is preferred here.

Despite concerns over its contradictions, the Brundtland report nevertheless brought about a significant contribution to the sustainability debate. Politically the report was also a major milestone: bringing sustainability to the forefront of the world agenda and making explicit an obligation on persons living in the current generation to consider those living in future generations. Of course this did not happen in isolation, but rather sat against a backdrop of popular environmental literature from the 1960s, 1970s and early 1980s (refer to, for example,

Herber (1962), Carson (1962), Ehrlich (1968), Schumacher (1973) and Catton (1982)), and the already existing use of the term in the World Conservation Strategy (International Union for Conservation of Nature, 1980). Indeed, the actual term 'sustainability' is said to have its roots in the idea of 'sustained yield', a major concept in forestry management for over two centuries (Wiersum, 1995). There had also been a marked increase in the popularity of the term following its use in the epoch-making *Limits to Growth* study by the Club of Rome (Meadows *et al*., 1972).

Today, two and a half decades after the release of the Brundtland report, the word 'sustainability' has grown to a very high level of popularity, with many possible definitions and interpretations. It is now said that modern attempts to define sustainability in the academic world vary considerably depending on discipline, professional background, and personal interests of those involved (Haberl *et al*., 2004). Outside academia, 'sustainability' and 'sustainable' have become ambiguous buzzwords. According to Jamieson (2008), for example, few words have become more heavily used or abused in government and business than 'sustainable'. Specifically, he states, "It is commonplace to stick the word 'sustainable' in front of almost anything, to talk of 'sustainable development, 'sustainable transport', sustainable housing', 'sustainable communities' and so on … its very ubiquity has robbed it of meaning, while corrupting the principles of activity to which it is attached" (Jamieson, 2008, p.iii).

It is therefore imperative that any attempt to apply the term 'sustainability' in relation to the biogeochemical cycles be precisely defined. The remainder of this chapter is thus devoted to: understanding the normative foundations underpinning sustainability (Section 2.2), identifying how the biogeochemical cycles contribute to these normative foundations (Section 2.3), clarifying the key biophysical laws underpinning the biogeochemical cycles (Section 2.4), and finally, establishing a key set of sustainability principles to guide the inquiry of the remaining chapters (Section 2.5).

2.2 The Normative Foundations of Sustainability

We cannot determine whether our current socio-economic system is sustainable without first addressing a preliminary and more fundamental question regarding what it is that we are seeking to sustain. Does sustainability, for example, require that all persons, including future generations, achieve a level of welfare at least as high as that currently held by persons within developed nations? Alternatively, is the obligation to future generations only to ensure that

their basic material needs are satisfied? In addition, given the high level of importance placed by many individuals on the preservation of natural areas, is there a special need to preserve environmental systems regardless of any contribution they may make to human material needs? Perhaps sustainability requires consideration of specific moral rights held by species other than humans, or the so-called 'intrinsic value' of the environment? There are no right or wrong answers to these questions, only different interpretations depending on one's value set and beliefs. Thus, as recognised by Baumgärtner and Quass (2010a, 2010b), sustainability is ultimately a normative notion concerning the way in which humans should act towards nature, and how they are responsible to one another and future generations.

By defining sustainability as a type of moral perspective, it becomes clear that we cannot evaluate progress towards sustainability based merely on a descriptive or functional analysis of environment-economy interactions. The definition of sustainability as applied in this thesis, its key principles and modes of assessment are thus based on a particular interpretation of what sustainability *ought* to entail. Specifically, this interpretation is based on the emerging field of 'Sustainability Economics'. Baumgärtner and Quaas (2010a, 2010b) identify the two key normative foundations of this field as *justice* and *efficiency*, which are in turn interrelated through the concept of *welfare.* These three concepts are considered further in Sections 2.2.1 to 2.2.3 below.

2.2.1 Justice

With reference to Becker (2009), Baumgärtner and Quaas (2010a, p.445) identify three specific types of *justice*: (1) justice between humans within the same generation (intragenerational justice); (2) justice between humans of different generations (intergenerational justice); and (3) justice between humans and nature (biocentric ethics).[9] Without a doubt, a core motivation in undertaking the work described in this thesis has been to contribute towards justice of the second type, i.e. intergenerational equity. Although the obligations on humanity to address issues of intragenerational inequity are certainly of equal importance, this has simply not been a core focus of this research; the global scale of the research and the methodologies developed are much better suited to consideration of distributional justice across time rather than within generations.

[9] There are, arguably, also other types of justice that are of relevance to sustainability, including inter-cultural justice and inter-gender justice. Neither of these topics are a focus of this thesis.

The third type of justice specified above reflects a belief that animal species, even plants and entire natural systems, may possess value 'in themselves', irrespective of their practical use to humans (e.g. Leopold (1949), Næss and Sessions (1984)). Most modern Western ethical theories, however, share the assumption that value must ultimately be reduced to matters of interest or concern to humans (Routley and Routley, 1979; Lockwood, 1997). Thus, a non-human object does not require moral consideration in and of itself, but only so far as it is perceived as contributing to the welfare of someone.[10] Nevertheless in recent years, with a growing group of environmental philosophers, the idea that values are determined solely through the interests of humans has been increasingly questioned (e.g. Routley and Routley, 1979; Callicott, 1985; Rolston, 1988).

This is a fascinating line of enquiry and it may prove that many people, even non-philosophers, agree that nature holds value. However, at least at this stage of the philosophical discussion, it is unclear as to what recognition of this value entails, i.e. in terms of people's moral obligations towards nature. What, for example, is the appropriate mode of conduct when a conflict arises between the interests of people and the 'interests of nature'? How do we ascertain nature's interests if these must be determined outside human reference? While it is beyond the scope of this thesis to address these questions in full, it is worth noting that the thesis does apply an anthropocentric lens in its interpretation of sustainability. In any case, provided we conceive of human well-being as critically dependent on nature, it may be of little consequence whether one takes an anthropocentric or ecocentric viewpoint towards sustainability (Pelletier, 2010).

Recognising that sustainability requires justice between people of different generations, leads us to the next important question, "What is the definition of, and criteria for, justice?" The term justice is often applied in general usage to mean the affirmation (or process therefore) of rights and obligations, or as a synonymous concept to 'fairness' and 'equality'.[11] Importantly, in the context of obligations towards future generations, Birnbacher (2006) distinguishes two contrasting paradigms: the optimistic and pessimistic. The optimistic paradigm is said to be characteristic of the main currents of Enlightenment philosophy, Marxism, and neo-classical economic theory and regards responsibility for future generations primarily as an obligation to

[10] Note, however, that human welfare is recognised as being advanced not only through practical-technological uses of environmental resources, but also through its satisfaction of contemplative (theoretical, religious or aesthetic) attitudes.

[11] For example, the first four definitions for justice given in the Concise Oxford English Dictionary are: (1) just conduct; (2) fairness; (3) the exercise of authority in the maintenance of right; and (4) judicial proceedings.

prolong a more or less reliable process of progress. It is, however, the pessimistic paradigm, which sees future generations in a potentially worse position than present generations, that forms the basis of many ecological interpretations. According to this paradigm, responsibility is of a conservative nature, involving primarily an obligation to *maintain the status quo*, be it of a technological, economic or cultural nature. While under the optimistic paradigm, the emphasis is on taking best advantage of opportunities; under the pessimistic paradigm the emphasis is on minimizing risks of imminent disaster.

The objective of achieving equity across generations, through ensuring each generation maintains some minimum standard (usually benchmarked by the current situation) is certainly a common theme within the economics literature relating to sustainability. Solow's (1974) paper, published shortly after the release of the *Limits to Growth* study, is often viewed as the first formal economic analysis of sustainability (Pezzey and Toman, 2005).[12] A key aim of this paper was to determine the conditions under which total consumption, taken to represent utility, could be sustained across time (because of factor substitutability and technological progress)[13], despite declining levels of non-renewable resources. This body of inquiry continued in much of the subsequent literature on the economics of sustainability, including the theoretical contributions by Hartwick (1977, 1978a, 1978b), Solow (1986), and Asheim (1986).

From an ethical point of view, however, many question the sufficiency of maintaining a *total* level of utility/welfare in the context of a global growth in population (Birnbacher, 2006). If

[12] It is, however, worth noting that numerous other economists have paid more than a cursory glance at the concept of sustainability. Early classical economists Thomas Malthus and David Ricardo, for example, were concerned with human population growth in the face of land scarcity. In his 1803 *An Essay on the Principle of Population*, Malthus foresaw an absolute scarcity effect where the finite nature of land would act as a binding constraint on population and economic growth. He forecast a resulting catastrophic decline in human population. Ricardo (1817), in a more rigorous analysis of this problem, asserted that land scarcity would be subject to diminishing marginal returns with a gradual reduction in the scale of the economy as it tended toward a 'steady state'. In his 1848 *Principles of Political Economy* J.S Mill also analysed this problem, accepted Ricardo's notion of diminishing marginal returns, but suggested the emergence of a 'stationary state' that might be offset by technological progress.

[13] Barnett and Morse (1963) tested the implications of natural resource scarcity on extraction costs and market prices. They found that resources were steadily reducing in price relative to labour and furthermore were becoming less scarce; a consequence of diminishing returns being overcome by discovery of additional reserves and creation of substitutes. Authors such as Weinstein and Zeckhauser (1975), Pindyck (1978), and Heal and Barrow (1980) have corroborated these results, while Solow (1974), Kamien and Schwartz (1978) and Dasguta and Stiglitz (1981) have gone further, arguing that it might be optimal to deplete a finite resource if technology and substitutes exist to replace it. Nevertheless, commentators such as Chapman and Roberts (1983), Hall *et al*. (1986), Norgaard (1990) and Ekins (2000) note that technology and substitutes are bound by physical laws, suggesting there is no reason why the trends identified by Barnett and Morse *inter alia* may continue into the future.

the obligation on the current generation is only to maintain a non-declining supply of utility, then individual members of the next generation will not be afforded the same level of welfare, simply on the basis that the population is of a greater size. Thus, non-declining *per capita* utility is now a more widely used indicator of sustainability than total utility (Pearce and Atkinson, 1993; Beckerman, 1994; Dasgupta, 2002; Nordhaus, 2001).

When setting out the defining objectives of sustainability it is now also quite common to speak of maintaining the *opportunity* or *capacity* to produce non-declining per capita utility, rather than maintaining non-declining per capita utility itself (Pezzey and Toman, 2005). In one of the most popular economic texts on sustainability, Neumayer (2013, p.8), for example, defines sustainability as maintaining "the *capacity* [my emphasis] to provide non-declining per capital utility for infinity". Even going back to *Limits to Growth*, the state of 'global equilibrium' sought by the authors is one where "each person has an equal *opportunity* [my emphasis] to realize his individual human potential" (Meadows *et al*., 1972, p.24).

One of the reasons for focusing on capacity or opportunity rather than actual attainment of utility/welfare is that it is impossible to know the needs and desires of future generations. On a related point, each generation has no control over how future generations will use the capacity they inherit, and one must not demand more from a generation than it can possibly achieve (Neumayer, 2013). Other commentators (e.g. Solow (1974), Richter (1994) and Dasgupta (1994)) have also expressed a concern that a constant utility over time requirement would imply that voluntary sacrifices undertaken by the current generation enabling future generations to enjoy higher utility are not permitted, if it means lowering the utility of the current generation below that of future generations. By phrasing sustainability in terms of the capacity to produce utility, this definitional problem is avoided (Neumayer, 2013). This approach also sits much more comfortably with the notion of 'freedom of choice', which is also strong normative concept in economics.[14]

[14] According to the Capability Approach developed by Sen *inter alia* (refer to Sen (1992, 1999, 2009)), for example, acting freely and being able to choose among alternatives is an integral part of well-being. Justice is therefore not restricted to the issue of resource distribution but includes freedom and, more precisely, freedom of choice (Ballet *et al*., 2011).

2.2.2 Efficiency

For many, the term economic *efficiency* has come to mean simply maximising production of market goods and services, given finite levels of resources (Bromley, 1990). It is, however, clear that Baumgärtner and Quaas (2010a, p.447) rely on a much wider concept of economic efficiency, in particular quoting a definition given by Robbins (1932, p.15), according to which economics "studies human behaviour as a relationship between [given] ends and scarce means which have alternative uses". The authors then explain that efficiency is not a primary goal in itself. Rather, it is a secondary goal justified by some other higher priority normative goal; a point also made by Ballet *et al*. (2011). Baumgärtner and Quaas (2010a, p.447) then note that "satisfaction of human needs and wants", which "typically serves as the normative goal of economics", is an example of one such goal, while "[s]ustainability, interpreted as inter- and intragenerational justice and justice towards nature" is another.

This question that now confronts us is whether this implies that the goal of allocating resources so as to best satisfy human needs and wants, or put a little differently, 'maximising human welfare', becomes redundant under sustainability economics. Surely, it does not. The concept of justice, at least as it is specified above, is alone not a sufficient foundation to sustainability. It could imply that the current generation is free to use resources unwisely or wastefully, so long as the same standard of welfare is maintained. Alternatively, and taken to the extreme, it therefore would not matter if persons lived at bare levels of survival, so long as each generation was treated equal. Although we may disagree with the modes of measuring and evaluating human welfare that are commonly used (e.g. consumption of market goods and services), a concern with producing the greatest possible welfare, with the least possible means, must also be considered to be a worthwhile foundation for sustainability.

2.2.3 Welfare

The above discussion has shown that the concept of *welfare* is central to sustainability, although thus far the term welfare has been used interchangeably with the terms 'utility' and 'satisfaction of human needs and wants'. Well-being is another term that is also often used. The concept of welfare has various interpretations. One commentator has stated, "There are at least as many views on how the welfare of individuals should be compared as there are authors who write on the subject" (Binmore, 2009, p.540). Until relatively recently, economics

was dominated by 'The New Welfare Economics'[15] (Bowles and Gintis, 2000). While it is beyond the scope of this thesis to provide a summary of this branch of economics, one can note that a core attribute of New Welfare Economics is its focus on achieving efficiency in allocating economic outputs through market mechanisms and enlightened government intervention. Efficient allocation is understood to be that which satisfies the Kaldor-Hicks compensation test (Hicks, 1939; Kaldor, 1939), i.e. if those who stand to gain are able to compensate those who stand to lose, and still be better off (a potential Pareto improvement), then it is considered to be justified. Welfare, as usually defined under this approach, is a function of personal utility levels as revealed by observed (market) behaviour. Furthermore, welfare rankings are made independent of the way utilities of different individuals compare with each other, or in other words, 'interpersonal comparisons' of utility are not possible. Where a decision may cause a gain in the welfare of one individual at the cost of another, this is considered entirely the domain of the political process.

It is not surprising that many have found this 'hands off' approach of New Welfare Economics unsatisfactory for addressing real world problems. As Sen (1970, p.50) put it, "nothing much of interest can be said on justice without bringing in some interpersonal comparability." Of more importance than the incompleteness of the New Welfare Economics as a normative basis for decision-making, are the significant theoretical challenges inherent in the conclusions made under this approach (Scitovsky, 1941; Boadway, 1974; Chipman and Moore, 1978; Bromley, 1990; Suzumura, 1999). Over the last two decades these difficulties have spurred a new interest in welfare-related research. This includes the Capability Approach developed by Sen and others (refer to Sen (1992, 1999, 2009)) and the new field of 'happiness studies' (e.g. Dixon (1997), Ng (1997), Frey and Stutzer (2002) and Layard (2005)).

It is not the intention of this thesis to contribute to the philosophical, theoretical or methodological debate regarding how best to define and measure human welfare. Rather, the intention is to determine whether human welfare depends on the functioning of the Earth's biogeochemical cycles. If we are convinced that such a relationship exists, this would then place obligations on us to manage interactions with these cycles to ensure justice towards future generations.

[15] Also known as general equilibrium theory, Walrasian welfare economics, or neo-Walrasian economics. Although most critics of economic theory use the general term 'neoclassical', today many economists who might call themselves neoclassical are also against the Walrasian system (Gowdy, 2007).

2.3 The Global Biogeochemical Cycles and their Contribution to Human Welfare

When economists contemplate the importance of ecological resources or systems to human welfare, they often speak of 'natural capital' and 'ecosystem services'. This section introduces these two concepts, as well as the specific role of biogeochemical cycles in contributing to human welfare.

2.3.1 Capital-based Perspectives on Sustainability

From an economic perspective, the requirement to maintain welfare *opportunities* for future generations leads towards consideration of the amount and quality of *capital* maintained. If capital is defined quite broadly as 'any item with capacity to provide welfare', then we can also conceive of 'natural capital' as any item within nature that can contribute to welfare, including "non-renewable and renewable resources, plants, species, ecosystems and so on" (Neumayer, 2013, p.9). In the case of biogeochemical cycles, which are an entire functioning system, the concept of capital must be very broad – covering all the various components (e.g. stocks of organic and inorganic materials, stocks of bacteria, plants and other organisms, genetic information, and so on) and the various relationships between these components. Nevertheless, given that ecosystems are often referred to as natural capital, there appears to be no reason why we should not also refer to the biogeochemical cycles as natural capital.

Capital-based approaches to sustainability are usually grouped into one of two categories, namely: *weak sustainability* and *strong sustainability* (Neumayer, 2013). According to the *weak sustainability* approach, a key requirement for sustainability is the maintenance of the sum of manufactured and natural capital from generation to generation (Hartwick, 1978a; Solow, 1986). However, empirical applications tend to focus on measurement of sustainable income or net capital accumulation rather than on direct estimation of the capital stock (Stern, 1997). Under the weak sustainability approach, it is assumed manufactured capital can be substituted for natural capital and thus depletion of natural capital is of no consequence provided there is sufficient accumulation of manufactured capital to compensate.

Various arguments have, however, been put forward to dispute the proposition that the weak sustainability approach, on its own, is a sufficient condition for sustainability (refer to Turner and Pearce (1992) and Stern (1997)). From a precautionary perspective, it is argued that we are largely ignorant of the potential detrimental consequences of depleting natural capital and

that natural capital loss is often irreversible. It is also contended that the ability to substitute manufactured capital for natural resources is limited by the physical laws of nature. A minimum quantity of energy is required to transform matter into economically useful products, and ultimately this must be supplied from the environment. Furthermore, it is simply not possible to produce an ever-expanding level of material output, from an ever-decreasing quantity of material input. Thus, the economy must ultimately be sustained by some level of renewable resources. Additionally, it is claimed that natural capital provides basic life support functions and cultural and amenity goods and services for which there are no substitutes possible via the provision of manufactured capital.

The *strong sustainability* approach is more difficult to define, as there are a number of interpretations available. A shared characteristic of the approach, however, is the assumption that natural capital is fundamentally non-substitutable with other forms of capital (Neumayer, 2013). Pearce and Turner (1990), and colleagues at the London Environmental Economics Centre, have further refined this characteristic by arguing that while it may be possible to substitute between natural and manufactured capital, there are certain stocks of 'critical natural capital' for which no substitutes exist (Turner and Pearce, 1992).

Strong sustainability proponents have been further grouped under two different interpretations (Neumayer, 2013). Under the first interpretation, the focus is on preserving the aggregate *value* of natural capital, with related sustainability indicators usually involving some type of aggregation of resources using monetary valuations. Recognising, however, that various types of natural capital may not substitute for each other and thus a single aggregate valuation is problematic,[16] the second interpretation focuses instead on preserving the

[16] Indeed, finding a theoretically defendable approach to the measurement of all capital is a long-standing problem for economics. During the 1960s, via the so-called 'Cambridge controversy', economists at the University of Cambridge critiqued neoclassical models of economic production and growth by making clear the difficulties in measuring diverse units of capital and incorporating them into formal economic analysis (refer to Pearce and Turner (1990)). It was pointed out that neoclassical approaches relied on price as a means of adding up disparate objects such as buildings, tractors and machinery, meaning that the level or 'quantity' of capital could not be ascertained independent of price. Additionally, the circularity between capital price and quantity was noted. Under neoclassical economics, the value of a capital good depends on the *present value* of the increase in output *across time* made possible by that good. In order to ascertain the present value of future output, an interest rate is required. However, to ascertain the interest rate, knowledge of the quantity of capital is required. This effectively means that the quantity of capital depends on the price of capital, capital price in turn depends on the interest rate, and the interest rate depends on the capital quantity. Although the difficulties in finding robust measures of capital stocks highlighted by the Capital controversy were framed in terms of manufactured capital, these difficulties apply also to natural capital stocks.

physical stocks of natural capital itself. Not surprisingly, no author has put forward a condition requiring *all* physical stocks of natural capital to be maintained (Pezzey and Toman, 2005). Instead, the various conditions proposed require maintenance of the *minimum stocks* of natural capital (Faucheux and O'Connor, 1995), key *functions* of natural resource stocks or preservation of *critical* natural capital Ekins (2003). This thesis is situated within Neumayer's second group of strong sustainability perspectives. In these regards it is recognised that the provision of ongoing opportunities for human life and well-being is vitally dependent on the maintenance of key environmental functions. Furthermore, supported by the ecological and systems perspectives outlined below, the provision of such functions is likely to depend on the maintenance of critical stocks of natural capital that allow environmental systems to persist within states below certain critical thresholds or tipping points. Furthermore, as there is considerable uncertainty regarding the nature and placement of such thresholds and the capacity of environmental systems to withstand change, a precautionary approach is required.[17]

2.3.2 Global Biogeochemical Cycles as Ecosystem Support Services

The concept of ecosystem services, coined in the 1980s and made popular particular through contributions from Costanza *et al*. (1997b), Daily (1997), and its use in the Millennium Ecosystem Assessment publications, is also frequently used as the 'lens' for understanding and communicating the multifaceted contributions of nature to human welfare. Clearly, ecosystems services are related to natural capital, with the former being a flow concept and the latter a stock concept. The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003, p.5) defines ecosystem services as "the benefits people obtain from ecosystems. These include provisioning, regulating and cultural services, which directly affect people, and supporting services needed to maintain the other services". A diagram depicting the various linkages between ecosystem services and elements well-being (Figure 2.1) also complements this classification.[18] Important to note is that biogeochemical cycling processes, labelled 'nutrient cycling' in Figure 2.1, sit within the supporting services group, and thus do not contribute to human welfare *directly*, but rather *indirectly* by supporting all other

[17] In line with these conclusions, it is interesting to note that the strong sustainability approach has also been recognised as having a strong connection to the 'safe minimum standards' (Ciriacy-Wantrup, 1952; Bishop; 1978) or 'precautionary principle' (Howarth, 1997) approaches to sustainability (Stern, 1997).

[18] Various other ecosystem frameworks have also been proposed. Particularly noteworthy is 'The Economics of Ecosystems and Biodiversity' (TEEB) approach hosted by the United Nations and supported by numerous government agencies (TEEB, 2010).

ecosystem services. As such, biogeochemical cycles are often referred to also as among the "basic life support systems of the earth" (see, for example, Krautkraemer (2005)).

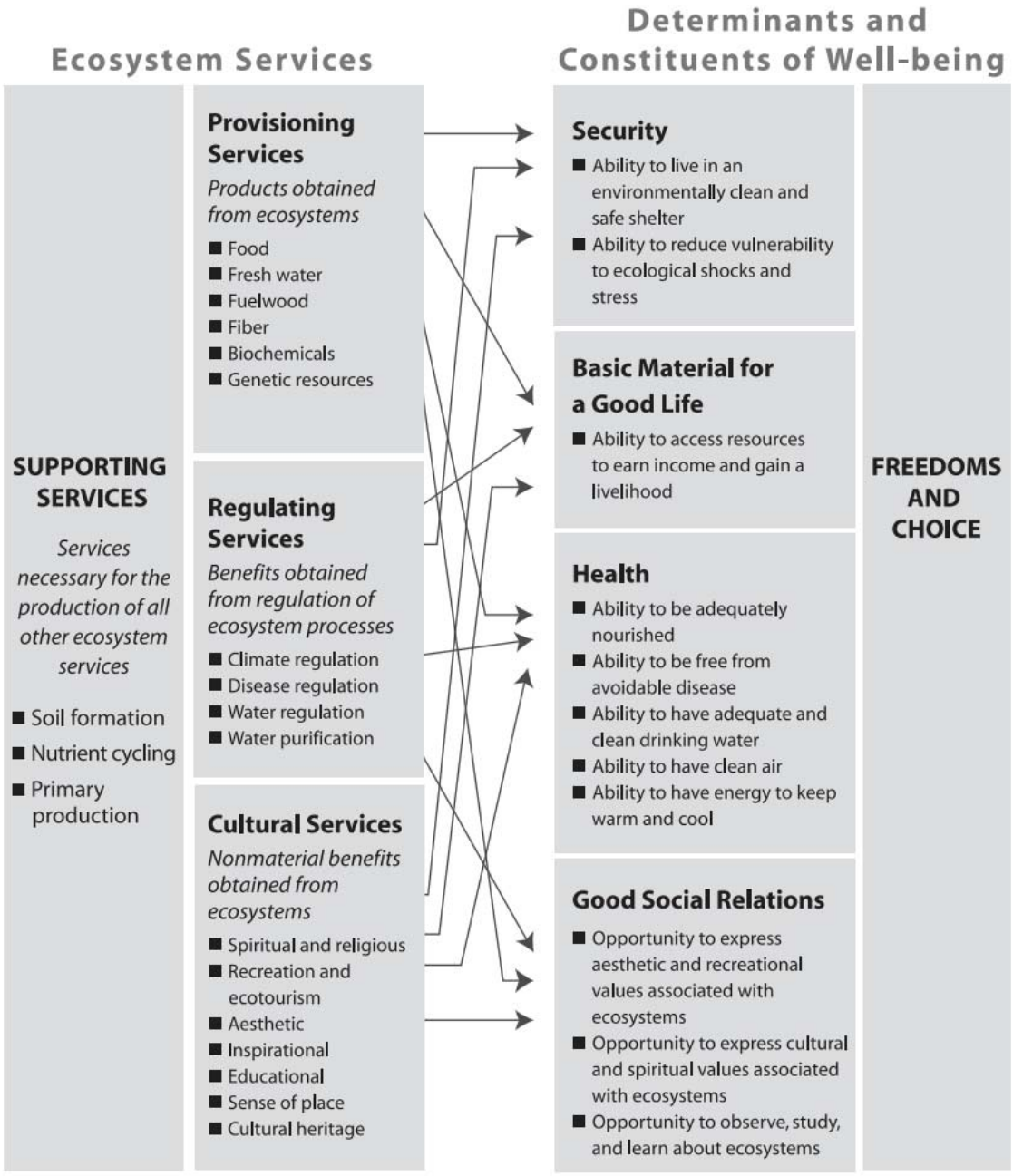

Figure 2.1 Millennium Ecosystem Assessment Conceptual Framework

Source: Millennium Ecosystem Assessment (2003, p.5).

Other authors have sought to expand and further develop the Millennium Ecosystem Assessment framework, including provision of insights regarding the way in which ecosystem services translate into elements of well-being as depicted by the arrows in the diagram (refer to, for example, Duraiappah (2004) and Polishchuk and Rauschmayer (2012)). However,

because of their indirect nature, their link to human welfare is somewhat more difficult to explain and measure and thus supporting services have generally received less attention in the ecosystem services literature than other services (Perrings, 2006; Zhang *et al*., 2010).

Boyd and Banzhaf (2007), in an attempt to standardise definitions for the purposes of environmental welfare accounting and performance assessment, put forward a revised definition of ecosystem services focusing only on *final* services. According to their definition, final ecosystem services are "components of nature, directly enjoyed, consumed, or used to yield human well-being" (Boyd and Banzhaf, 2007, p.619). Their distinction between end-products and intermediate products is fundamental because, as the authors explain, "many, if not most, components and functions of an ecosystem are intermediate products in that they are necessary to the production of services but are not services in themselves." Importantly, the authors also define biogeochemical cycling (they use the term 'nutrient cycling') as an ecological function that, while valuable, is intermediate to the production of final ecosystem services.

Regardless as to whether biogeochemical cycling is categorised as an ecological function necessary for the production of ecosystem services, or as an ecosystem service in itself, the fundamental importance of biogeochemical cycling does not appear to be in any doubt. According to Smil (2002, p.249), for example, "the importance of global biogeochemical cycles is easily stated: all economic systems are just subsystems of the biosphere, dependent on its resources and services. The biosphere cannot function without incessant cycling of scarce elements needed for prokaryotic and eukaryotic metabolism". Similarly, Melillo *et al*. (2003, pp.1,7) state "[t]he grand cycles of C, H, O, N, P, S and perhaps as many as 25 other elements sustain life on earth … As these elements move through the environment, sometimes in inorganic forms and sometimes in organic forms, they interact in a variety of ways. These interactions can be direct, as in situations where an element serves to chelate, immobilize, or catalyse a reaction involving another, or they can be indirect, as in cases where a nutrient limitation imposed by one-element influences the rates at which other elements cycle within and among ecosystems. Many of these interactions have consequences for basic ecosystem processes, such as organic matter production by plants and decay of organic materials by microbes, and so affect the way the world works in fundamental ways".

2.4 Biophysical Perspectives on Sustainability

While we may suggest that the maintenance and enhancement of human welfare is the ultimate goal of sustainability, the above discussion has shown that we are only likely to move towards this goal if we can understand and appreciate humans as ecological entities. Thus, we are intimately connected with and affected by the rules and boundaries of the biophysical environment. Numerous scholars within the ecological economics discipline also stress this same conclusion. Rees (1996, p.197), for example, contends, "Economic assessments of the human condition should be based on, or at least informed by, ecological and biophysical analyses". Similarly, Pelleteir (2010, p.1890) argues that that "the ecological economic actor must be understood first as a member of the relevant human *and non-human natural* communities which mutually constitute the conditions necessary to her existence and well-being. From this vantage point, distributive justice in economic organizations begins with the promotion of economic configurations that ensure the wellbeing of the ecological community as a whole."

In the remainder of this section, an overview of ecological and biophysical concepts relevant to sustainability of the global biogeochemical cycles is discussed. This includes the laws of thermodynamics, and the concepts of carrying capacity, resilience, and non-equilibrium ecological systems. Additionally, important insights from Systems Theory, which help in integrating the thermodynamic and ecological concepts, are considered.

2.4.1 The First and Second Laws of Thermodynamics and Mass Conservation

Thermodynamics is the science of the nature of relationships between heat and other forms of energy and their conversion, flow direction, and availability for work (e.g. Zemansky, 1997). The first and second laws of thermodynamics are of most importance to sustainability.[19,20] The first law is commonly referred to as the law of conservation of energy and provides that while

[19] The third law of thermodynamics provides that as a temperature of absolute zero (-273°C) is approached, the extraction of energy from a system or its environment becomes increasingly more difficult.

[20] Georgescu-Rogen's (1977a, 1979) statements on material entropy have been popularly termed the 'fourth law of thermodynamics'. He proposed (1979, p.1039) that in a closed system, such as the biosphere, "material entropy must ultimately reach a maximum". In other words, the quality of matter decreases as waste products become scattered and unusable. The notion of material entropy has, however, been subject to significant debate (see, for example, Bianciardi *et al*. (1996), Corning (2002)).

energy may be transformed during processes, it can be neither created nor destroyed.[21] The second law is commonly referred to as the 'entropy law' (Georgescu-Roegen, 1971). Rephrased for interpretation by non-physicists, it can be formulated as, "[a] substance will always come to a unique equilibrium with its environment. The path it takes over time to reach this equilibrium is reproducible, depending only on the applied constraints and its initial condition" (Fisk, 2011). This law implies that if a system is in a low entropy (ordered) state, it will tend to move toward a state of maximum entropy (disorder). In addition, processes are irreversible in the sense that an injection of energy that is greater than the amount of energy liberated by the process in the first place, is required. An important corollary of this law is that open systems may only establish, and sustain, a state of low entropy (non-equilibrium) by creating flows of negative energy to the environment via the dissipation of energy and matter (Prigogine, 1967; Glansdorff and Prigogine, 1971; Prigogine, 1977; Schneider and Kay, 1992). Economic and environmental systems, which are among the class of systems often referred to as 'dissipative structures' (Schrödinger, 1944) and exist at a state far from thermodynamic equilibrium, hence depend on large amounts of high-quality energy supplied from outside the respective systems.

The law of conservation of mass or the so-called Mass Balance Principle (Ayres and Kneese, 1969) is often viewed as an outcome of the first law of thermodynamics. Strictly speaking, however, the first law only applies to the conservative nature of energy transformations. Regardless, the principle is important in helping convey the idea that, barring accumulation in the production process, all materials extracted from the environment for use in economic activities must ultimately be balanced by the returned of materials to the environment in the form of residuals and unwanted materials (Ayres and Kneese, 1969; Kneese *et al*. 1970).

Informed by the first and second laws of thermodynamics and the Mass Balance Principle, the economy is seen as an open system embedded within the global biophysical system (e.g. Gilliland (1977)). Since the world only has a finite mass, growth in the physical size of the economy must come at the expense of the environment. In a physical sense, the size of the economy also cannot exceed the capacity of the biosphere to produce material and energy

[21] As explained by authors such Faber *et al*. (1987), Binswanger (1993) and Ruth (1993), three types of systems are recognised under thermodynamic analyses: (1) an isolated system involving neither energy nor matter exchange across a system boundary; (2) a closed system under which only energy may cross a system boundary; and (3) an open system under which both matter and energy may cross a system boundary. The first law implies that energy net transfer of energy across a system boundary as either heat or work, is equivalent to the net change in the internal energy of the system.

resources, or assimilate residuals. The economic system is further viewed by economists such as Ekins (1994), Reid (1995) and Wetzel (1995) as operating essentially via the transformation of inputs of low entropy materials and energy (e.g. fossil fuels, minerals) into outputs of degraded, high entropy materials/energy (e.g. gaseous emissions, waste heat). Note that the second law also implies that complete economic recycling of wastes and residuals is impractical, at least not without significant inputs of high quality energy to the recycling processes (Georgescu-Roegen, 1971, 1976; Daly, 1987; Bianciardi *et al*., 1996). The system is further constrained in that processes within the environment (including the biogeochemical cycles) that act to absorb high entropy matter/energy expelled by the economy and regenerate useful resources are themselves dependent on ongoing inputs of low entropy matter/energy from outside of those systems.

Such insights have had a wide influence within the sustainability literature (Ayres and Kneese, 1969; Georgescu-Roegen, 1971, 1977b; Victor, 1972; Daly, 1977, 1996, 2008; Perrings, 1987; Ayres, 1999; Odum and Odum, 2006). Daly (1992, p.16), for example, proposed a steady-state economy characterised by "constant stocks of people and artefacts, maintained at some desired, sufficient levels by low rates of maintenance 'throughput', that is, by the lowest feasible flows of matter and energy from the first stage of production (depletion of low entropy materials from the environment) to the last stage of consumption (pollution of the environment with high entropy wastes and exotic materials." He further proposed the principle of appropriate 'scale' as one of the three core principles for an efficient, just and sustainable economics (Daly, 1992). Scale, in turn, is defined as physical volume of throughput via the flow of low-entropy raw materials from the environment and the return of high-entropy wastes. More recently, Pelletier (2010, p.1892) states that the principle of scale is legitimised when "[i]nformed by thermodynamic principles, which dictate the most basic conditions necessary to ecological integrity across scales of organization".[22] Research on how to conceptualise the scale of human activities is now widely recognised as a core agenda for the discipline of ecological economics (Røpke, 2005; Rockström *et al*., 2009).

Importantly, thermodynamic principles have had a significant impact within the field of ecology. To a large extent this is attributable to the work of the Odum brothers beginning in

[22] Although thermodynamic principles are frequently credited as a major source of inspiration and thought on the physical conditions limiting the scale of human enterprise (Hammond, 2004), contributions to the scale debate have arisen out of more than thermodynamic principles alone. Paul Ehrlich's book *The Population Bomb* (1968), for example, focused particularly on population growth and the battle to feed humanity.

the 1950s (Odum, 1953).[23] Key concepts from ecology are outlined separately in the next section.

Clearly thermodynamic considerations, along with the Mass Balance Principle, also underpin the field of Industrial Ecology.[24] As stated by Bringezu and Moriguichi (2002, p.79), the paradigm vision for the field is "a sustainable industrial system characterized by minimized and consistent physical exchanges between human society and the environment, with internal material loops driven by renewable energy flow". Material Flow Analysis (MFA), a methodology within Industrial Ecology, is concerned with the tracing of socio-economic materials and energy flows, and assessment of changes in relevant ecosystems related to these flows. The use of the Mass Balance Principle within MFA helps avoid overlooking important uses of resources and/or their release to the environment (Lifset and Gradel, 2002). As also noted by Haberl *et al*. (2004), a key advantage of MFA is that it is able to link data and models used to analyse socioeconomic systems (e.g. IO analysis and general equilibrium modelling) to data and models used for environmental systems (e.g. box-flow models). MFA is further recognised as a key tool for assessing the resource efficiency of economies, in particular providing valuable insights into analyses concerned with evaluating the rate of decoupling of natural resources and environmental impacts (Fischer-Kowalski *et al*., 2011). Decoupling, which has been defined simply as "breaking the link between 'environmental bads' and 'economic goods'" (OECD, 2001),[25] is now one of the most frequently promoted objectives of national and international agencies in relation to sustainability (refer to, in particular, UNEP *et al*. (2011)).

[23] See, in particular, the later work of H.T. Odum (1983). Thermodynamic concepts and consequences are also discussed by Morowitz (1968), Brooks and Wiley (1988), Wicken (1985), and Zotin (1985), among others.

[24] Industrial Ecology, which emerged during the 1990s (Ayres and Simonis, 1994; Erkman, 1997), is now said to encapsulate sufficient tools, studies, publication, and resources to characterise itself as a discipline (Ehrenfeld, 2000, 2001). A central tenet of Industrial Ecology is that Nature is a model for industrial ecological systems (Isenmann *et al*., 2008), that is, as put by Cleveland (1999, p.148), "to look to the natural world for models of highly efficient use of resources, energy and byproducts".

[25] Decoupling has been further categorised as either 'relative' or 'absolute' (UNEP *et al*., 2011). Relative decoupling occurs when the growth rate of an environmentally relevant parameter is lower than the growth rate of a relevant economic parameter. Under absolute decoupling, however, the environmentally relevant parameter declines, irrespective of the growth rate of the economic parameter. Thus, absolute decoupling can only occur when the growth rate of resource productivity exceeds the growth rate of the economy.

2.4.2 Ecological Viewpoints on Sustainability

Carrying Capacity

The concept of carrying capacity is defined within the ecological literature as "a measure of the amount of renewable resources in the environment in units of the number of organisms these resources can support" (Roughgarden, 1979, p.305). More generally, the concept is understood as the "maximum population of a given organism that a particular environment can sustain" (Allaby, 1994). Defined as such, carrying capacity is a function of both the level of resources provided by the environment and the level of resources required by the particular organism under consideration.

The carrying capacity concept also has a relatively long history of application to humans. Among anthropologists and geographers interested in primitive agricultural societies, for example, carrying capacity is the maximum number of people that a given land area will maintain in perpetuity under a given system of usage without causing land degradation (Allan, 1949; Brush, 1975). However, while the concept may be relatively straightforward, its actual application to modern societies is highly complex. This is due not only to difficulties in calculating environmental capacities, but also to variations in the types and quantities of resources consumed due to social and cultural factors and evolution in production technologies (Daily and Ehrlich, 1992). Nevertheless, the concept has been highly influential within the sustainability literature. Of particular importance is the adoption of the term as part of the Ecological Footprint (EF) indicator, where it is defined as the "the maximum rates of resource harvesting and waste generation (the maximum load) that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems" (Rees, 1996).

Over recent years, concepts such as carrying capacity, which imply some type of fixed goal for society, have been criticised for conveying an outdated stability-oriented view of ecosystems (Haberl *et al*. 2004). There has thus been a movement towards a more dynamic view of the concept, acknowledging that carrying capacity may alter over time, and/or focus instead on concepts such as risk and resilience (Quental *et al*. 2011).

Non-Equilibrium Ecology and Resilience

Before the mid-1980s equilibrium theory dominated ecology. One of its central ideas was the concept of succession.[26] This is essentially a process through which a community of animals, plants, and microorganisms progressively develop from an embryonic to a mature climax state conceptualised as relatively stable, diverse, energetically efficient, complex, highly developed in feedback control and characterised by low entropy and high levels of information (Odum, 1971; Kay, 1991). This 'equilibrium state' was thought to represent a structure that may, subject to exogenous perturbation, persist indefinitely. Under the equilibrium theory, ecosystems are maintained in a state of balance through the mechanism of homeostasis (Miller, 1995). Self-correcting feedback mechanisms ensure that if the ecosystem is perturbed it is returned to its original state.

In a two landmark papers, May (1972, 1974) demonstrated that communities that are more diverse are not necessarily more stable, as assumed under the equilibrium paradigm.[27] This was shortly followed by Holling's (1973) paper on resilience and stability in ecological systems, in which he illustrated the existence of multiple stability domains or multiple basis of attraction in natural systems. DeAngelis and Waterhouse (1987) furthered challenged the ecological paradigm. According their work, instead of assuming that a single equilibrium point exists, communities are pictured as existing in a spectrum with multiple states of relative stability. Such systems may switch to a new steady state when environmental perturbations force them beyond a certain threshold limit. Figure 2.2 demonstrates these ideas graphically. A community existing in an 'equilibrium' (probably better termed an 'attractor' (Carpenter, 2003)) is aligned to a ball positioned at point A of Figure 2.2. In this position, the ball may experience a small perturbation (force) such that it will return to the valley floor after a few oscillations. A later perturbation, however, may force the ball out of the valley to another location that may or may not be stable (points B, C, and D of Figure 2.2).

[26] The term ecological succession can be traced back to Frederic Clements (1916).

[27] May demonstrated mathematically 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" (May, 1972, p.414). Moreover, he demonstrated that the simplest of non-linear equations, as used to represent ecosystems, could produce chaotic, and therefore unstable, behaviour (May, 1974).

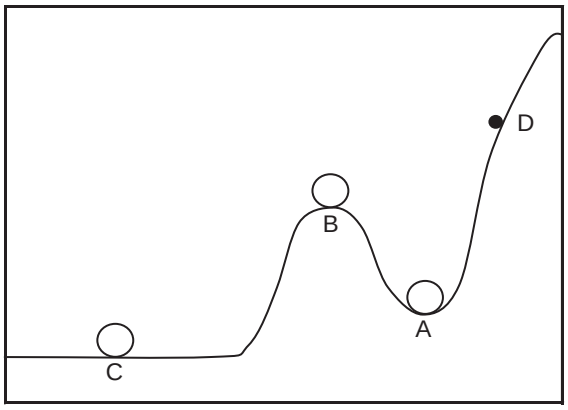

Figure 2.2 Non-Equilibrium and Equilibrium Points in Ecosystem Dynamics

Notes: 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).

Many empirical examples of regime shifts or multiple basins of attraction within ecology have now been presented. Very often, these examples involve situations of high human disturbance of ecosystems, and new or altered ecosystem states, which are less desirable in terms of their capacity to provide ecosystem services (Gunderson, 2000). From a risk perspective, the focus has been on maintaining ecosystems within lower and upper biophysical limits represented by floors and ceilings to avoid a potential transition to a new state. This type of reasoning has also had some influence on sustainability perspectives in relation to the biogeochemical cycles. According to Ayres (1993, pp.201-205), for example, "[a]ny disturbance to bio-geochemical cycles is *ipso facto* a threat to survival. A common characteristic of non-linear dynamic systems far from equilibrium is multiple branches or "attractors". It is possible under certain circumstances for a system to "flip" from one of these attractors to another. Because we do not know the stabilizing mechanisms for the climate or the various cycles in detail, we cannot know how big a perturbation it would take to move to another quasi-stable state or even to begin an irreversible slide toward the true equilibrium state which would not sustain life". The author also proposes that the condition for stability in these cycles is that "the stocks in each compartment, or reservoir, must remain constant (at least on average); and for this condition to be met the inflows into each compartment must be balanced exactly (on the average) by the outflows".

The concept of resilience emerged from a branch of ecology concerned with the study of populations in relation to ecological stability theory (Folke, 2006). Holling (1973, 1986, and 1995) introduced the concept of resilience as the capacity to persist within a stability domain

when subject to change. According to a more recent definition, resilience is "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Walker *et al*., 2004, p.2). Much of the ecologically oriented research on resilience has focused on identifying the conditions under which the buffering capacity of ecological systems is eroded, thus making these systems less capable of withstanding shocks. However, for coupled socio-economic and ecological systems, resilience research also focuses on learning and organisation dynamics that increase adaptability, i.e. the capacity of actors within a system to influence resilience (Kates and Parris, 2003; Clark *et al*., 2004; Walker *et al*., 2004; Folke, 2006; Hjorth and Bagheri, 2006).

According to Walker *et al*. (2004) actors can influence system resilience by: (1) altering the maximum amount a system can change before losing its ability to recover; (2) moving a system away from or closer to a threshold (i.e. altering the 'precariousness' of the system); (3) making a threshold more difficult or easier to reach by altering the 'resistance' of the system to change; and (4) managing cross-scale interactions. Although the research on social-ecological resilience is still exploratory and difficult to characterise due to its very broad nature, one can note that processes of visioning and scenario planning are often proposed as key tools in building resilience (e.g. Folke *et al*. (2002), Folke (2006)). In general, activities and policies that generate knowledge and learning are also emphasised, including those that "strengthen the perception of humanity and nature as interdependent and interacting … recognizing the existence of ecological thresholds, uncertainty and surprise" (Folke *et al*., 2002, pp.439-440). Given the relevance to this thesis, it is worth noting here that the selection and provision of relevant information, particularly indicators, is also recognised as one of the most powerful means of making system changes (Meadows, 1998; Hjorth and Bagheri, 2006).

2.4.3 Systems Thinking and Sustainability

Many commentaries on the topic of sustainability emphasise the importance of systems thinking and systems theory (refer to, for example, Suzuki, 2007; Senge *et al*., 2008; McKibben, 2010; Sterman, 2012). Systems theory is an interdisciplinary field of science concerned particularly with the nature of complex systems in nature, society, and science. The field originates from the late 1930s during a time of growing dissatisfaction with the reductionist approach of mainstream science. Despite the continuing success of reductionist science in helping to explain evermore processes and phenomena, the method remained particularly

unsatisfactory in dealing with complex situations with a great variety of 'variables' and not apt to analysis in terms of distinct causal mechanisms (von Bertalanffy, 1972).

Ludwig von Bertalanffy is generally considered the founder of systems theory. Among his most recognised work is the 1968 publication *General System Theory: Foundations, Development, Applications*. Together with other practitioners, von Bertalanffy set out to develop a body of theory comprising the set of general principles applicable to all 'systems' and their subclasses, irrespective of their particular kind (von Bertalanffy, 1968). Other important early contributions to the field came from Wiener (1948), Ashby (1956), von Neumann (1956), Boulding, (1965), and West-Churchman (1968) among others. Over recent decades, systems theory has grown and diversified into a vast range of subject matters, including ecological systems (Odum, 1983, 1994), organizational theory and management (Senge, 1990), sociology and socio-cybernetics (Luhmann, 1995) and software and computing (Yourdon and Constantine, 1979). Today, systems concepts have become so embedded into the thinking and working of researchers within a vast range of fields, that it is seldom viewed as a separate movement within science.[28] It would seem that systems theory or thinking can now be described as a particular paradigm. As with any paradigm, this greatly shapes the way in which the world is viewed, including the way in which problems are defined, the procedures used in analysis, and the criteria used to evaluate results (Kuhn, 1962).

Underpinning much of the recent work within ecology already described in the previous section, modern systems theory or thinking is strongly influenced by ideas of non-equilibrium and 'complex adaptive systems'. Such systems are characterised by non-linear behaviour, emergent properties and limited predictability. Table 2.1 below lists some of the most important systems ideas or theories relevant to this thesis and their resulting implications. As previously noted, systems concepts are integral to understanding the ecological and thermodynamic perspectives, and their connectivity, in relation to sustainability.

Broadly speaking, systems thinking leads towards the conclusion that sustainability is not a static goal or target to be achieved, rather it is an ongoing process of ensuring that the key 'viability' loops within a system, i.e. those that prevent exponential or run-away behaviour and return a system to a desired state (also termed balancing or negative feedback loops), remain functional (Hjorth and Bagheri, 2006). System resilience is "provided by several such loops,

[28] Note, however, that systems theory is still being extended, particularly through the work on chaos theory and dynamical systems.

operating through different mechanisms, at different time scales, and with redundancy – one kicking in if another one fails" (Meadows, 2008, p.76). Given limited certainty, limited predictability and the process of evolution within complex systems, maintaining and building resilience is an adaptive approach. It involves consistent modification or improvement of goals (moving targets) during a process of continuously learning and updating our understanding of the relevant system. Dynamic simulation models are frequently advocated for use as learning tools, as these help build both consensus about the nature and extent of problems and the intuition and understanding of complex systems, including identification of the feedback processes underpinning dynamic behaviour (Richmond, 1993; Sterman, 1994; Hjorth and Bagheri, 2006, Costanza *et al*., 2007).

Table 2.1 Key System Concepts and Implications

Topic	Sub-topic	Systems Concepts	Implications[1]
Definition	System definition	A system may be defined as a set of elements standing in interrelation among themselves and with the environment (von Bertalanffy, 1971).	The world itself can be thought of as a very large and complex system that includes the biogeochemical, socio-economic and other subsystems.
Nature of systems	Interactions	A system is not the sum of its parts, it is also the product of their interactions (von Bertalanffy, 1968; Ackoff, 1971).	The reductionist approach, consisting of disaggregating the effects of each element in a situation and identifying the discrete contribution of each element, may be unsuitable for analysis of sustainability and the global biogeochemical cycles.
	Emergence	Properties and behaviours of a system may emerge that, while obviously originating from the collective dynamics of that system's components, are neither to be found in, nor are directly deducible, from the lower-level properties of that system (Anderson, 1972).	
	Feedback loops	A system component can start a sequence of causes and effects that eventually loops back, so that each of the components in the loop indirectly influences itself. This is called a feedback loop. Any given system component may be the outcome of multiple feedback loops (Forrester, 1968).	The global biogeochemical cycles (including socio-economic interactions) are multi-loop, nonlinear feedback systems. Our cognitive maps of the causal structure of such systems are vastly simplified compared to the complexity of these systems themselves (Sterman, 2012). We cannot predict the behaviour of these systems, and decisions that result in an impact on these systems may lead to unanticipated side effects.
	Linear and non-linear relationships	The components of a system are related in a linear manner if changes in one variable always result in a proportional change to the other variable. Non-linear relationships result from responses that are not proportional to cause. In natural systems, linearity if the exception rather than the norm (Forrester, 1969).	
	Open and closed systems	A closed system is one that has no interaction with any element not contained within it, while an open system is one that exchanges flows (materials, energy or information) with the environment (von Bertalanffy, 1968).	Human economic systems are open systems interacting with the environment. Economic systems determine the rate and route of flows of resources and energy from the environment, and similarly, the rate and route of flows of waste back into the environment.
	Systems and thermodynamics	A closed physical system will always move towards a state of higher entropy. Open physical systems, however, may create and maintain a state of low entropy by continuous exchanges with their environment (Schrödinger, 1944; Ashby, 1947; von Bertalanffy, 1969; Prigogine, 1977).	The global biogeochemical cycles (including their socio-economic interactions) are, for all intended purposes, closed with respect to matter, but depend on the continuous supply of energy. These physical characteristics constitute ultimate constraints on the operation of these cycles.

Table 2.1 Key Systems Concepts and Implications (Cont.)

Topic	Sub-topic	Systems Concepts	Implications[1]
Complex adaptive systems	Self-organisation	Spotaneous patterns of organisation, such as whirlpools above drain holes or a flock of birds, are a key property of complex adaptive systems. Despite appearing stable, such structures tend to depend on non-linear feedback mechanisms, and are sustained far from equilibrium by ongoing inputs from outside of the system (Holland, 1975)	The overall patterns of material and energy flows under biogoechemical cycles are difficult to understand and control - they constitute a 'moving target'.
	Co-evolution	Complex adaptive systems constantly re-organise to find the best fit with the environment. As these systems exist within their own environment and are part of that environment, re-organisation also changes the environment (Holland, 1992)	
System thresholds, stability	Stability	Stability is measured by the response of a system to perturbation and is analysed with reference to state variables. Certain system, or sub-system, states may be more stable than others (von Bertalanffy, 1972).	Humans interact with and affect the global biogeochemical cycles. While these systems have shown to tolerate a degree of stress, there may be ultimate thresholds. Sustainability requires, at the very least, avoiding an irreversible transition to a new state that may exhibit conditions unsuitable for humankind.
	Attractors	An attractor is a state towards which a system tends from other states and corresponds to steady-state or equilibrium behaviour. A system can move through a state space with multiple attractors. Once in an attractor, a system will tend to remain there until there is an external event of sufficient force or sufficient internal drift to lodge the system from that attractor (Lorenz, 1963; Ruelle and Takens, 1971).	
	Critical points, bifurcation and thresholds	A critical point is the value of a control variable at which there is a qualitative change in system behaviour. An important type of critical point is a bifurcation point. Here, during the approach to a critical value, the system behaves in a characteristic and usually stable way. Beyond the bifurcation point, minutely different values of variables result in drastically different behaviours (May, 1977; Holling, 1978; Feigenbaum, 1980).	

Notes: 1. Each implication may correspond with more than one system concept.

2.5 Key Principles for Sustainability

Sustainability is defined in this thesis as the pursuit and enhancement of human welfare, while not compromising the ability of future generations to satisfy this same objective. Implicit in this definition are several key principles of sustainability distilled from the above literature review that are of particular relevance to the global biogeochemical cycles. These key principles are outlined in Table 2.2 below along with how they are addressed in this thesis. Note that many of the principles are interconnected, and thus contributions made with respect to one principle are often a contribution to other principles.

Table 2.2 Key Principles for Sustainability and their Application in this Thesis

	Principle 1: Decouple material and energy throughput from economic production	Principle 2: Use natural capital efficiently
Definition	Reduce the quantity of material and energy throughput required per unit of economic output.	Producing the greatest possible welfare with the least possible use of natural capital. In the context of the biogeochemical cycles, use of natural capital includes (directly or indirectly) depleting matter that takes time to be regenerated, or accumulating matter that takes time to be assimilated.
Rationale	Material throughput is the key link between human activity and the level of pressure placed on the biogeochemical cycles.	Efficiency serves to achieve sustainability. It provides for current and future welfare while helping to ensure that the means through which this is achieved, the natural capital that sustains life, remains intact.
Key Supporting References	Daly (1977, 1992b, 1996, 2008), Bringezu and Moriguichi (2005).	Baumgärtner and Quaas (2010a, 2010b).
Application of the principle in this thesis	*Chapter 5: Elemental Material Flow Accounts for the Global Economy* This establishes a set of material flow accounts (raw material use and residual production). From this baseline information, and the definitions and methods presented, we can consistently monitor future progress in decoupling. *Chapter 10: Ecocycle: An Integrated Environment-Economy Model of the Global Biogeochemical Cycles* Constructing and testing scenarios within the integrated model will help us to understand how patterns of material throughout may change, identify effective strategies for decoupling, and whether there might be unexpected consequences of policy options (e.g. Chapter 9 discusses the increasing loss of soil S associated with efforts to reduce use of fossil C).	*Chapter 5: Elemental Material Flow Accounts for the Global Economy* Understanding the flow of materials both within and between socio-economic and ecological systems, including their transformation into economic products is an important first step towards increasing efficiency. *Chapter 7: Is There Overshoot of Planetary Limits?* Provides a method for developing efficiency indicators for different economic goods and services, along with initial results. Such indicators assist in identifying where particular efficiencies exist and helps people to make informed consumption choices. *Chapter 10: Ecocycle: An Integrated Environment-Economy Model of the Global Biogeochemical Cycles* Provides an infrastructure to calculate indicators such as employment per unit of material use, or consumption of economic goods per unit or residual. Changes in these indicators over time can be tested under alternative strategies or policy options.

Table 2.2 Key Principles for Sustainability and their Application in this Thesis (Cont.)

	Principle 3: Maintain the economy within an appropriate scale relative to the biosphere	Principle 4: Maintain viability loops within the environment-economy system
Definition	The physical volume of matter throughput within the global economy should not exceed the capacity of the biogeochemical systems to regenerate the inputs and absorb the waste outputs.	Ensure multiple negative feedback structures exist within the environment-economy system
Rationale	The appropriate scale criterion seeks to prevent depletion or degradation of natural capital and carrying capacity, maintaining human perturbation of the biogeochemical cycles at safe levels.	Negative feedback structures help to regulate systems, avoiding otherwise exponential or run-away behaviour, and return systems to a desired state
Key Supporting References	Daly (1992) and Pelletier (2010).	Richmond (1993), Sterman (1994), Hjorth and Bagheri (2006), Meadows (2008)
Application of the principle in this thesis	*Chapter 7: Is There Overshoot of Planetary Limits?* New indicators are devised that measure the scale of human activities relative to the scale of biogeochemical processing, hence determining the extent of any 'overshoot' or 'undershoot' of biogeochemical processes. *Chapter 10: Ecocycle: An Integrated Environment-Economy Model of the Global Biogeochemical Cycles* Stocks and flows are incorporated within the model enabling us to translate Chapter 7's indicators into *dynamic* sustainability indicators. Both changes in the scale of the economy, and the biosphere, can be investigated under alternative possible futures.	*Chapter 8: A Dynamic Equilibrium Seeking Model of the Global Economy, Chapter 9: A Dynamic Biogeochemical Cycling Model of the Global Environment & Chapter 10: Ecocycle: An Integrated Environment-Economy Model of the Global Biogeochemical Cycles* Each of the dynamic modelling chapters contribute towards the development of dynamic simulation 'learning tools'. Virtual experimentation with such tools enables us to test and improve our understanding of system behaviours and identify current and potential feedback structures within the environment-economy system (e.g. initial trial runs have flagged the likely importance of diversity and redundancy in the economic system for coping with changing resource constraints and 'ironing-out' price fluctuations).

Table 2.2 Key Principles for Sustainability and their Application in this Thesis (Cont.)

	Principle 5: Build resilience within the socioeconomic-environmental system
Definition	Increase the capacity of the socioeconomic-environmental system to retain the same functions, structure and feedbacks when subject to disturbance.
Rationale	The aim is to avoid transition of the socioeconomic-environmental system to a less desirable state in terms of its ability to provide for current and future welfare.
Key Supporting References	Meadows (1998, 2008), Walker *et al*. (2004) and Folke (2006).
Application of the principle in this thesis	*Chapter 5: Elemental Material Flow Accounts for the Global Economy & Chapter 7: Is there Overshoot of Planetary Limits?* Various indicators are presented. Indicators are, themselves, tools of change and learning. *Chapter 10: Ecocycle: An Integrated Environment-Economy Model of the Global Biogeochemical Cycles* Provides capacity to investigate futures under alternative scenarios. Envisioning futures and actions that might attain, or avoid, outcomes helps us to learn and select resilient building strategies.

Notes: 1. Another popular example is the so-called 'rebound-effect' observed in relation to energy efficiency and improvements (Greening *et al*., 2000).

Chapter 3

A Framework for Modelling Coupled Economic and Global Biogeochemical Cycling Systems

3.1 Introduction

This chapter guides the remainder of the thesis by setting out a framework for understanding the global biogeochemical cycles, and how these interact with the global economic system. The chapter begins (Section 3.2) by presenting a conceptual overview of the global system as relevant to the study of biogeochemical studies, including consideration of exogenous inputs and outputs and key endogenous stocks, flows and interrelationships. Some preliminary system boundary and definitional matters are also discussed. Based on the conceptual overview, it is then possible to suggest a generic *static* system framework for biogeochemical cycles (Section 3.3). This framework is presented as a system diagram and full mathematical description of an 'Environmentally-Extended Social Accounting Matrix' (ESAM). Essentially the ESAM constitutes an accounting system for mass and monetary flows within, and between, the global environment and economy. Note that the ESAM underpins not only the static models and indicators developed within Chapters 4, 5, and 6, it also supports the dynamic models within Chapters 7, 8, and 9 through identification and definition of key system flows. By way of introduction to the ESAM, a brief overview is also provided of other static system models of environment-economy systems, principally in the field of IO analysis. The final components of the chapter (Section 3.4) are concerned with introducing the system modelling framework and techniques selected for the *dynamic* components of the thesis. In these regards, System Dynamics is selected as the principal modelling approach.

3.2 Conceptual Framework for the Global Environment-Economy System

3.2.1 A Note on the Global Socio-Ecological System

The field of Ecological Economics has been highly influential in promoting a view that the human economy is part of a wider ecological system (Costanza, Daly and Bartholomew, 1991). Jones (2011, p.31), for example, describes the 'sustainability egg' analogy whereby the

economy is depicted as an open subsystem (the egg yolk) of the Earth's biosphere. It is embedded within the natural environment (the egg white), which is "organic and dynamic but essentially closed except for limited energy and material inputs from the sun and other celestial and subterranean sources and reflected energy outputs".

Some authors, however, have cautioned against taking a view of society as simply a subsystem of the biosphere (Haberl *et al*., 2004). The argument put forward is that while societies may be connected to the biosphere via material/energy flows, they have emergent properties that cannot be fully understood by analysing simply the biophysical structures sustaining them. Weisz *et al*. (2001), for example, in an attempt to better understand sustainability, views society, "as a hybrid of the realm of culture, of meaning, of community and of the natural world". Haberl *et al*. (2004) thus define a social-ecological system as consisting of two separate spheres of causation (Figure 3.1). The natural or biophysical sphere is governed by natural laws, while the other sphere is a cultural or symbolic sphere of causation.[29] According to the authors, sustainability "refers to the interaction process between nature and culture which can only proceed indirectly, via the biophysical structures of society" (Haberl *et al*., 2004, p.201). These biophysical structures are, in turn, physical components of society such as human populations, physical infrastructure and livestock. Within this thesis, such biophysical structures, and the processes governing their interactions, as classified as belonging to the anthrosphere,[30] of which the economy is a key component.[31] Although in a physical sense the economy sits within the environment, many of the processes that operate within the economy, and thus cause change in biophysical structures, are the result of cultural factors.

[29] Refer to Schellnhuber (1999).

[30] Others have used the term 'society'.

[31] It is important to note that a wide definition of economic systems is applied, whereby an economy is broadly a system of management and allocation of scarce resources to meet human wants and needs. This means that an economy is more than the activities and transactions that can be described by formal market prices. The gathering of household firewood and subsequent combustion of that fuel, for example, may occur outside the formal market system, but these activities are nevertheless considered to be undertaken by the economy, and cause matter to enter and then exit the economic system.

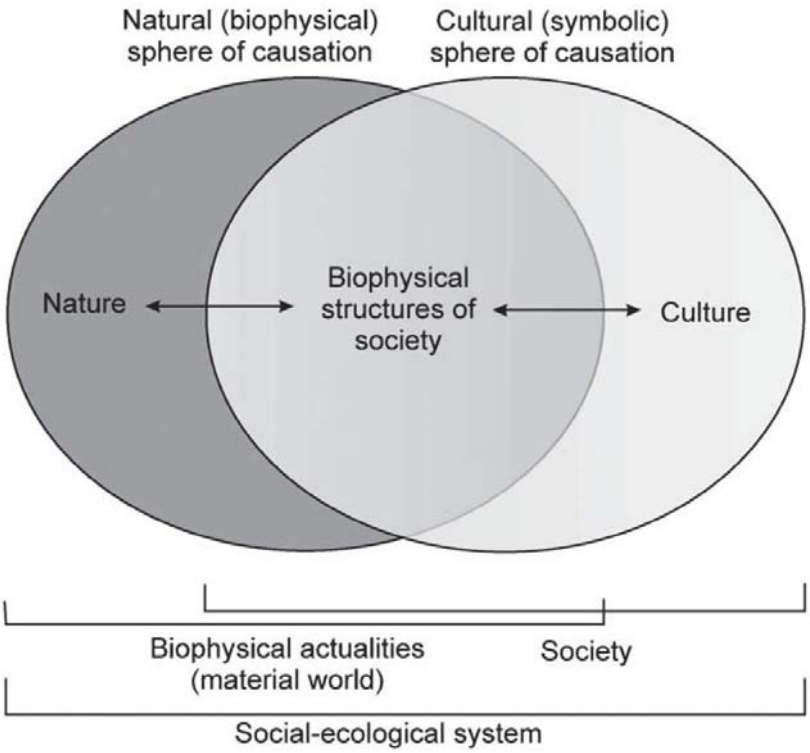

Figure 3.1 Spheres of Causation for Social-Ecological Systems

Source: Haberl *et al*. (2004).

3.2.2 The Global Environment-Economy System

Figure 3.2 diagrammatically depicts the global environment-economy system as conceptualised in this thesis. Key features of the diagram include: (1) the exogenous energy inputs (e.g. solar energy, crustal heat and tidal energy) and waste heat output of the Earth's environment-economy system; (2) the physical flow of mass/energy/information within, and between, the environment and economy; and (3) the flow of money within the economic system. Each process involving mass is subject to the Mass Balance Principle[32] (Ayres and Kneese, 1969). Furthermore, it is worth noting that if energy transformations were to be fully accounted for, then energy would also be conserved within each process. This system diagram is explained in full below. Specifically, Section 3.2.3 describes the key stocks and flows, while Section 3.2.4 reflects on system boundary issues.

[32] Ayres and Kneese (1969), in their seminal paper *Production, Consumption and Externalities*, created the 'Materials Balance Principle', which is often also referred to as the 'Mass Balance Principle'. The principle, "which is a direct consequence of the first law of thermodynamics, states that, at each physical transformation process, or stage of a process-chain, the mass of inputs (including any unpriced materials from the environment) must exactly equal the mass of outputs, including wastes" (Ayres, 1996, p.3). Ayres (1996) notes that batch processes, or continuous processes with time variability, may result in temporary accumulation in stocks, which must also be accounted for when applying the principle.

3.2.3 System Stocks and Flows

Physical Economic Stocks and Flows

Matter and energy enter the economy in the form of raw materials and then, following transformation with the economy, circulate in the form of goods, services and labour. A small portion of this matter/energy becomes tied up within reserves of capital (e.g. buildings, machinery, vehicles), as well as various stocks of economic goods (e.g. food, clothing, fuel reserves). A significant portion enters waste products, some of which is recycled or re-used within economic activities. Eventually all matter/energy, however, crosses the economic system boundary as an output to the environment in the form of residuals and waste heat. The concept of 'industrial metabolism' (Ayres, 1989; Ayres and Simonis, 1994) establishes an analogy between the economy and ecosystems on a material level. Note, however, that while in the biosphere organisms close material loops by cycling resources and wastes interchangeably, economic processes establish only part of a loop, and must depend on the biosphere to continuously provide raw materials and assimilate residuals.

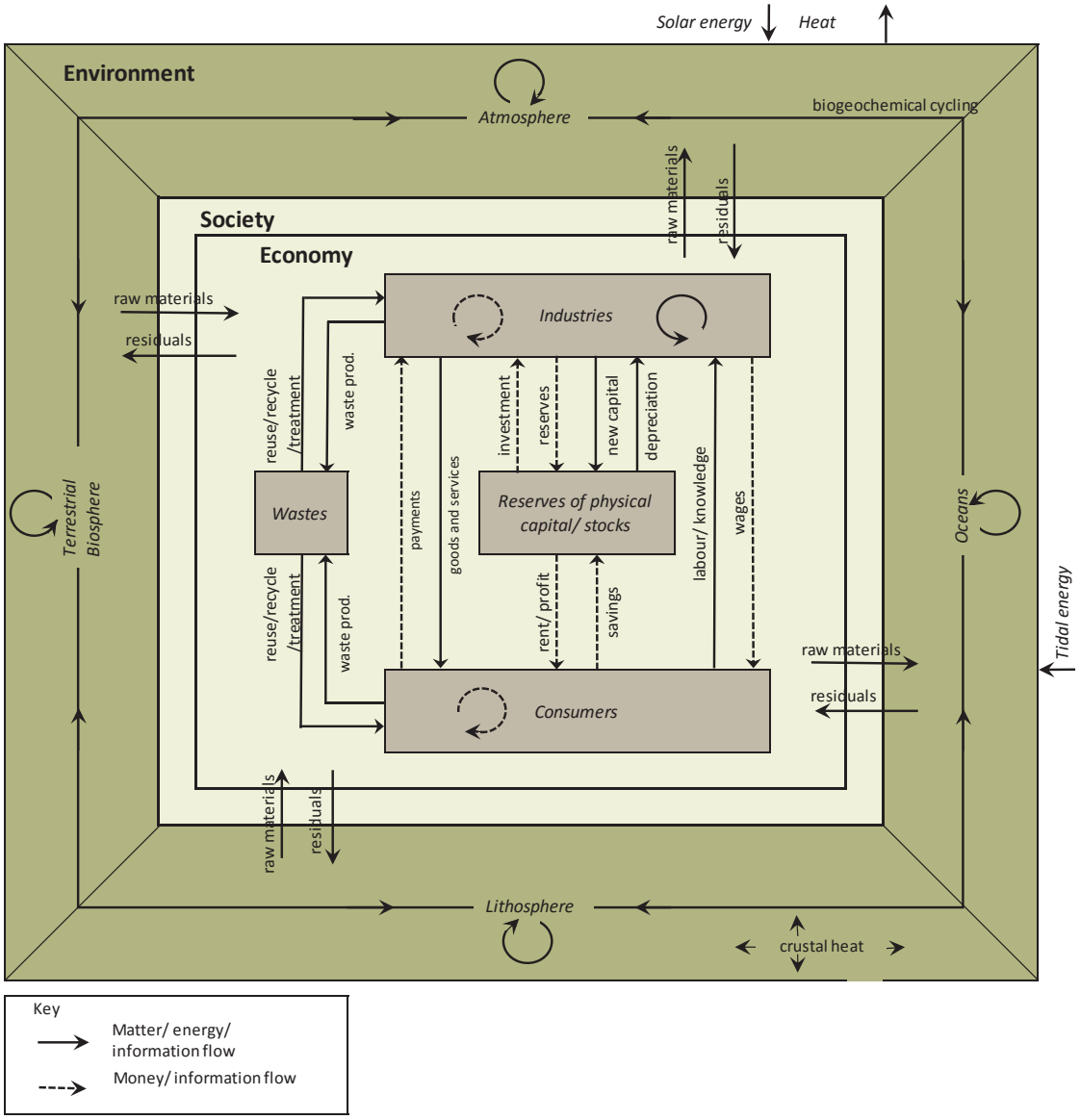

Figure 3.2 The Environment-Economy System

Physical Environmental Stocks and Flows

To assist in conceptualisation, the environment is divided into four separate compartments or spheres – the atmosphere, oceans, terrestrial biosphere, and lithosphere. Each of these spheres, in turn, is comprised of a number of major stocks, for example, vegetation and soils in the case of the terrestrial biosphere. The biogeochemical cycles encapsulate the sum of all exchanges occurring between such reservoirs within each sphere, as well as exchanges between the spheres themselves. External energy inputs from the sun are the primary energy flows 'driving' the biosphere system, although energy from other sources including crustal heat and tidal flows are also important. Living organisms have an essential role in many of the processes responsible for adding this useful energy to the biogeochemical cycles. A key process, for example, is photosynthesis where enzyme-catalysed reactions enable conversion of incoming electro-magnetic radiation from the sun into chemical energy stored in organic matter. In their entirety, the biogeochemical cycles are highly complex and self-organised systems, maintained at a disequilibrium state with respect to thermodynamics (Schlesinger, 1997).

Monetary Economic Flows

Within the economy, flows of money are generally in the opposite direction to flows of materials, energy and information.[33] Monetary units are exchanged for economic commodities, hours of work, information and knowledge, and rights to deplete or degrade capital. These exchanges are often made possible by a generally accepted system of prices that provides a basis for comparison and transaction. As aptly put by de Rosnay (1979, p.26), "[p]rice is the expression of this value of exchange; it is a 'value meter' of distinctly practical use, since it constitutes an item of information that, while artificial, is essential in the functioning and regulation of the economic machine."

The demand for material goods and services, referred to as economic commodities,[34] is the primary driver of matter/energy flows through the global economy. The majority of these commodities are allocated through private markets to meet individual interests and needs. Demands for commodities also arise, however, from collective actions aimed at servicing

[33] Note that not all material, energy or information flows have a corresponding monetary flow as many exchanges are not captured within formal market systems.

[34] While the term 'commodity' is used throughout this thesis to refer to substances from both economic and environmental systems, it should be noted that it is not the desire of the author to imply that all environmental substances should, or even could, be subject to market valuation and related monetary exchange.

shared or community needs. Two principal types of economic agents are depicted within Figure 3.2. Producers (i.e. economic processes or 'industries')[35] are responsible for the production of economic commodities, while consumers (largely households) use economic commodities for the satisfaction of human needs or wants. We may note that industries also typically consume economic commodities, but this is generally for the sole purpose of producing other economic commodities.[36] Following the UN System of National Accounting (European Commission *et al*. 2009, Sections 4.17, 4.20, 4.21), governments act both as producers and consumers of economic commodities on behalf of people. Furthermore, households, while principally conceptualised as consumers, also engage in production via the provision of labour and knowledge. Income received in exchange for factors of production enables agents to save money, leading to the accumulation of capital.

The extent to which components of the environment are made available for economic use is determined by ethics and values, which guide rules and regulations governing human behaviour towards the environment as well as voluntary acts of stewardship. Information on the state of the environment also influences economic behaviours. Declining oil reserves, for example, may contribute towards growing commodity prices, as might imminent crop shortages following a natural disaster. Finally, land-use change, which has been referred to as 'colonization of ecosystems' (Fischer-Kowalski and Haberl, 1998, Krausmann *et al*., 2003), typically manifests as an extension of the biophysical structures of the economy at the expense of the environment. For example, the replacement of uncultivated forest ecosystems with crop ecosystems, or the removal of freshwater systems on enlargement of urban areas.

3.2.4 System Boundaries

The above system diagram depicts a boundary between the economy/society and the environment. In reality, however, there is no obvious demarcation between the environmental and economic systems. In the context of MFA, the European Communities methodological guide defines inputs from the environment to the economic system as "the extraction or movement of natural materials on purpose and by humans or human-controlled means of technology (i.e. involving labour)" (European Commission, 2001, p.17). Furthermore, outputs from the environment to the economy occur once "society loses control over the

[35] For the most part, the terms economic process and industry can be used interchangeably. Note, however, that since the economy is defined broadly to include not just the formal market economy, non-market transformations undertaken by households might also be termed an economic process.
[36] The consumption of commodities by industries is often referred to as 'intermediate consumption'.

location and composition of the materials" (European Commission, 2001, p.17). There are however a number of borderline cases that must be settled by convention. The rearing of domestic livestock, for example, is usually considered a process occurring within the economy, while fertilizer applied to agricultural land is usually considered an output to the environment, because subsequent dispersion and soil processes are difficult to measure and not completely under human control (European Commission, 2001). These conventions are also followed in this thesis.

There are a number of bio-matter stocks that could be classed as either within the environment or economy. The three most important cases are bio-matter consumed by domesticated animals, forests, and crops. Ideally, following the system definition given above, the pastures and forests over which humans maintain very strict control would be included within the economy. However, due to difficulties in distinguishing natural pastures and forests from cultivated pastures and forests within various databases, in this thesis these stocks are classified as within the environment. This means that the consumption of vegetation by domestic animals and the harvest of timber constitute inputs to the economy. Crops, on the other hand, are classified as a stock within the economy, meaning that the cross-boundary flows represent the nutrients required for the bio-metabolism of these plants.

3.3 Static System Framework

This thesis adopts an Environmentally-Extended Social Accounting Matrix (ESAM), developed out of concepts and principles of IO analysis, as the core static system framework. Once populated with data from the global environment economy system, this becomes the static system model of the global biogeochemical cycles. Before describing the components of the ESAM in detail, it is helpful to step back a little, and review some of the reasons for constructing static models of environment-economy systems, and also previous work that has been undertaken in these regards.

3.3.1 A Short Introduction to Static Models

A model is anything used to represent an object or system (Forrester, 1971a, 1971b). Many formal models are static in nature. While under a dynamic model the state of a subject system will change with reference to time, a static model does not depict time-dependent changes in

the state of the system.[37] Static modelling is concerned particularly with describing system *structure*, whereas dynamic modelling focuses more on representing *behaviour*. A static model of the biogeochemical cycles would be used, for example, to answer questions such as "How many Pg of C were exchanged between the atmosphere and vegetation associated with terrestrial net primary production in 2004?" or "How many tonnes of raw materials and residuals were respectively extracted from, and discharged to, the natural environment in 2004?" While such questions may appear modest in nature, without such basic information on the state of a system it is extremely difficult to build understanding of the current system and develop consensus on the nature and extent of problems and the need for any behavioural change. Beyond such queries, there are several interrelated reasons why building static models may be important:

- *Contributing to indicator development*. Indicators are partial reflections of reality that provide a means of monitoring complex systems. Typically, the information used to produce indicators is a subset or aggregation of information contained within a system model.
- *Undertaking structural analysis*. Static analysis can be used to understand the structurally complexity of the system, including establishing key system components and their size, extent, and connectivity within the system. Moreover, with mathematical transformation, it is often possible to understand the key interdependencies, both direct and indirect, that exist within a system.
- *Undertaking comparative statics*. Static models may be used to formulate theories about changes in the value of variables, "between two states of rest" (Kuenne, 1963, p.14), or pre and post an event (Fisher, 1983).
- *Setting initial conditions*. A snapshot of a system at rest, or for a given point in time, is often used to populate initial conditions and establish baselines, benchmarks or points of reference for validating or calibrating dynamic models (Ford, 1999).

It is worth noting that static analysis has been applied widely in both ecology and economics. Ecologists, for example, have studied the structural relationships using such methods as food webs and chains, Network Analysis (Hannon, 1973),[36a] Energy Analysis (Hannon, 1982; Hannon, 1991), Emergy Analysis (Odum, 1996; Brown and Ulgiati, 2004; Voora and Thrift, 2010), and

[37] Note, however, that time is likely to be important in defining a particular static model. For example, an IO model for an economic system for the calendar year 2014 will be different from an IO model for the calendar year 2015.

Environs Analysis (Patten, 1981, 1982). Similarly, economists have also applied static analysis to study the environment-economy system through IO (refer to Cumberland (1966), Isard (1968), Daly (1968), Leontief (1970), Victor (1972) and Strassert (2000)), optimisation (refer to, for example, Bonaventura *et al*. (2009), Hritonenko and Yatsenko (2013)) and econometrics (refer to, for example, Cuaresma *et al*. (2010)).

3.3.2 Input-Output Tables, Supply-Use Tables and Social Accounting Matrices

This section provides a brief description of IO models and their associated building blocks (SUTs) and key derivatives (environmental IOs, PIOTs and environmental SAMs). Appendix A provides further details on IO including its history, mathematics, underpinning assumptions and major environmental extensions.

IO has its origin in the work of Nobel Laureate Wassily Leontief who, in 1936, published the first IO table for the US economy, followed later by his publication *The Structure of the American Economy* (Leontief, 1941). The starting point for IO analysis is an IO table for a given period, typically developed from a nation's System of National Accounts. An IO table records, in matrix form the flow of commodities, generally expressed in pecuniary terms, from all producing sectors to all purchasing sectors, sales to final demand, and the value of primary inputs to each sector. The IO table serves two purposes (Richardson, 1972; Hoekstra, 2005): (1) a descriptive tool delineating the relationships between producers and consumers within an economy; and (2) given certain assumptions, an analytical model for measuring socio-economic and, if augmented with environmental information, environmental impacts arising from changes in an economy.

SUTs, also referred to as 'commodity-by-industry' or 'commodity-by-process' accounts, are the building blocks of the IO accounting system (Stone, 1961), now recommended as the basis for national accounting by the System of National Accounts handbook (United Nations, 1968; United Nations, 1993). As explained by Miller and Blair (2009), the underlying observation is that industrial processes (i.e. industries) use commodities for the production of other commodities. Furthermore, commodities are consumed in the satisfaction of final demands. A major advantage of SUTs, over IOs, is that they thus allow multiple commodities to be produced by a single economic process or industry. However, before data within a SUT framework are transformed into a model for analytical purposes,[37a] including a standard IO table, analysts must apply a set of assumptions regarding the relationship between industry

outputs and commodities. Selection of an appropriate assumption is a source of controversy within the IO literature. It may lead, for example, to the generation of negative coefficients in the resulting analytical models. Appendix B of this thesis is devoted entirely to constructing analytical IO models from SUTs under various sets of assumptions.

In the late 1960s, IO practitioners began to extend the IO framework to incorporate not only economic transactions, but also within environment and environment-economy transactions. This enables assessment of both the socio-economic and environmental implications of economic change. Appendix A provides further details on how this was achieved along with key frameworks developed including those by Cumberland (1966), Daly (1968), Isard (1968), Leontief (1970), and Victor (1972). These models illustrated how raw materials (or 'free goods') from the environment were utilised in economic production, and similarly, how residuals (or 'externalities') are expelled by the economy back into the environment. A related IO extension is the recording of transactions in purely physical (i.e. mass/energy) terms. PIOTs record not only market transactions, but also the vast number of non-market flows occurring within the economy and at the economy-environment interface, in physical terms. In this way, PIOTs illustrate the 'industrial metabolism' of an economy.

SAMs are an accounting framework, often viewed as an extended form of IO analysis (refer to, for example, Miller and Blair (2009)). Double entry bookkeeping underpins both IO and SAM models, where what is incoming into one account, is matched by outgoing from another account (Martínez-Anguita and Wagner, 2010). However, while an IO model focuses on describing flows within product and services markets, a SAM also includes flows occurring within primary input markets where the transactions for value added factors of production occur, including wages and salaries to employees, entrepreneurship or profits returned on invested capital, taxes paid to government and other transfers (Miller and Blair, 2009).[38] A SAM thus provides a complete description of the circular flow of income within an economy, including the relationship between income and consumption for each actor within the accounts. In Chapters 4 and 5 of this thesis, an environmentally extended SAM, known as ESAM, is developed.

[38] Refer to Pyatt (1991, 1994a, 1994b and 1999) for a review of the rationale for, and development of, SAMs.

3.3.3 Formal Description of the Environmentally-Extended Social Accounting Matrix

Simple Matrix Representation

To begin, Figure 3.3 presents the flows within the environment-economy system in a matrix form. Importantly, four core sub-matrices are identified. First, the upper left corner of the matrix depicts the 'within-economy' system flows (e.g. money, information, materials and energy). The bottom left corner depicts flows from the environment to the economy (e.g. raw materials), while the top right corner depicts flows from the economy to the environment (e.g. residuals). Finally, the bottom right corner depicts flows within the environment itself.[38a] This relatively simple matrix representation of the environment-economy system, which is developed in full below, conceptually underpins the full ESAM developed in this thesis.

From \ To	Economic System	Environmental System
Economic System	Within economic flows	Economy to environment flows
Environmental System	Environment to economy flows	Within environment flows

Figure 3.3 Simple Matrix Representation of the Environment-Economy System

Source: Adapted from Daly (1968), Costanza *et al*. (1997a), and Martínez-Anguita and Wagner (2010).

Comprehensive Commodity-By-Process Matrix Representation

The full ESAM static system framework is set out in a commodity-by-process matrix format in Figure 3.4. It has some similarities to the economic SUT framework originally proposed by Stone (1961, 1966), and subsequently, adapted by Victor (1972) to include ecological commodities. The matrix structure is further compatible with the SUT framework recommended for development of National Accounts by the United Nations (1999),[39] although with some adjustments in light of the limited data available on intra-sectoral accounts.[39a] Note also that the within-economy components of the framework are expanded to constitute a

[39] Not only does the UN System of National Accounts require standardised practices in the development of SUTs, but also applies internationally recognised commodity and industry classifications such as respectively the Central Product Classification (CPC) and International Standard Industrial Classification (ISIC) systems. This potentially enables ESAM to be replicated, given available data, at a finer spatial resolution, e.g. a multi-regional analysis based on national or continent boundaries.

SAM, through full specification of income and expenditure within the primary input, and final demand, accounts.

The framework is a large matrix, broken down into a number of sub-matrices and vectors. The row and column categories that are used to demark the separate sub-matrices and vectors are referred to broadly as sectors. The income accounts for each sector are detailed across the rows, while the expenditure accounts are recorded down the columns. Note also that the static framework is concerned with specification of system flows. This means that a specific period, over which the flows are measured, must first be specified before the matrix can be populated with data. In this thesis, data availability determined that a 2004 calendar year be applied as the base year for the ESAM.

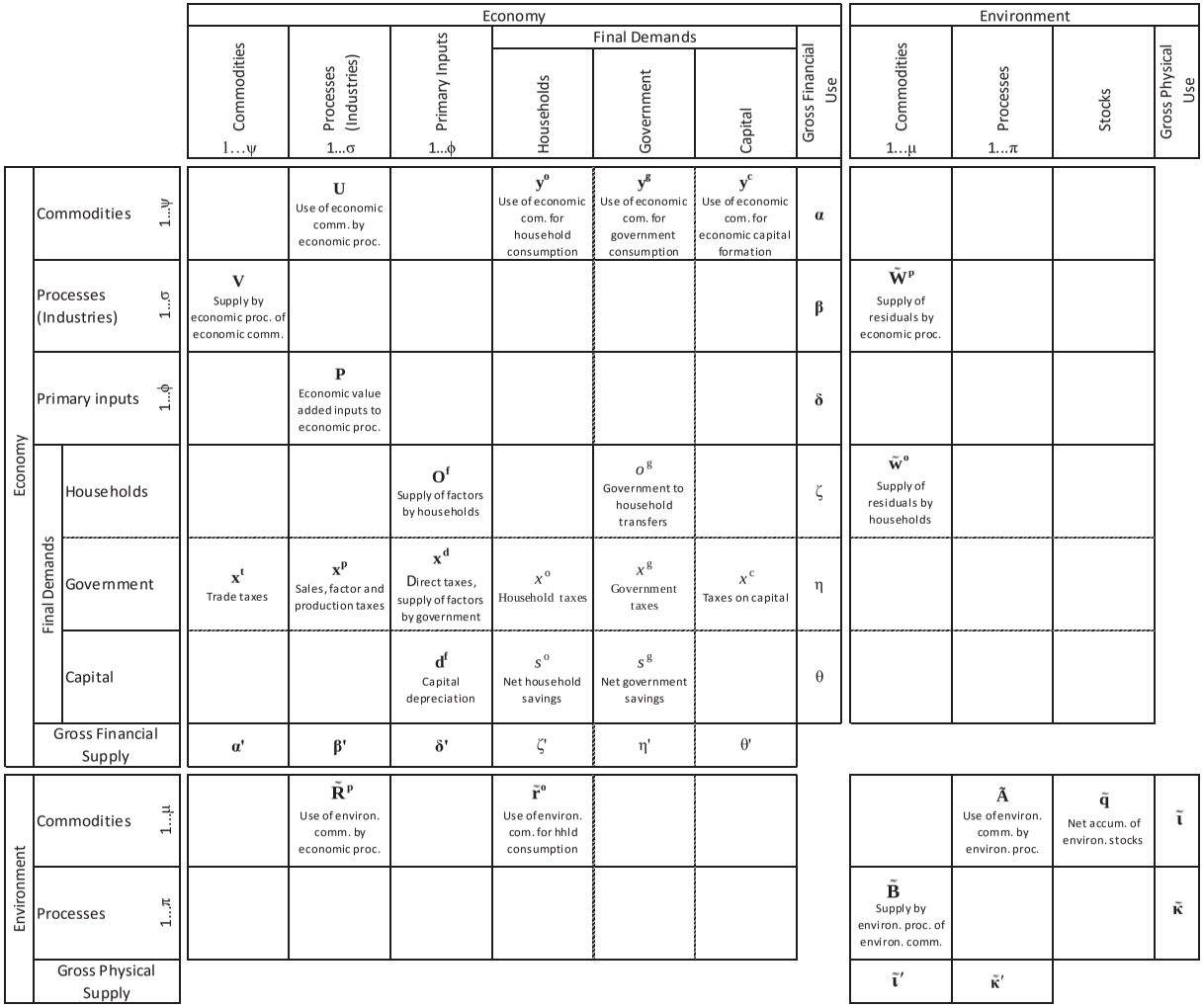

Figure 3.4 Structure of the Environmentally-Extended Social Accounting Matrix

Adapted from Victor (1972) and McDonald (2005).

Component Matrices and Vectors

The detailed description of the static system framework begins with the commodity income accounts consisting of matrix $\mathbf{U}$ (ς x σ), as well as vectors $\mathbf{y^o}$ (ψ x 1), $\mathbf{y^g}$ (ψ x 1), $\mathbf{y^c}$ (ψ x 1), and $\boldsymbol{\alpha}$ (ψ x 1). The matrix **U,** sometimes called the Use Table, defines the use of economic commodities by industries, with an element $u_{i,j}$ representing the value of commodity i used by economic process or industry j ($i \in \{1...\psi\}$, $j \in \{1...\sigma\}$). Together vectors $\mathbf{y^o}$, $\mathbf{y^g}$, and $\mathbf{y^c}$ represent the complete set of final demand categories, valued inclusive of taxes or purchasers' prices. An element $y^o{}_i$ represents the consumption of commodity i by households, an element $y^g{}_i$ denotes the consumption of commodity i by government, and $y^c{}_i$ the use of commodity i for capital formation. Finally, the gross commodity demanded vector, $\boldsymbol{\alpha}$**,** is found by summing the row elements, i.e.

$$\alpha_i = \sum_j u_{i,j} + y^o{}_i + y^g{}_i + y^c{}_i \,. \tag{3.1}$$

The SAM accounting method requires careful balancing between income and expenditures within an economy. A key principle is that all purchases of a given commodity by all processes must equal the supply of that commodity. In mathematical notation, $\alpha_i = \alpha'_i$, where α'_i is defined as,

$$\alpha'_i = \sum_j v_{j,i} + x^t_i \,. \tag{3.2}$$

In an analogous manner within economy accounting identities may also be formed for economic industries (i.e. $\beta_j = \beta'_j$), primary inputs (i.e. $\delta_h = \delta'_h$), and for each final demand category (i.e. households, government and capital, respectively as $\zeta = \zeta'$, $\eta = \eta'$, and $\theta = \theta'$).

The next row in Figure 3.4 contains the income accounts for economic industries. The production relationships within the economy are captured within the Supply Table, matrix $\mathbf{V}$ (σ x ψ). An element $v_{j,i}$ represents the annual output of economic commodity i (valued exclusive of trade taxes) by domestic industry j. In this way, matrix $\mathbf{V}$ describes the source of economic

products to the economy. The vector **β** (σ x 1) describes the total economic output of each industry and is defined as,

$$\beta_j = \sum_i v_{i,j} \,. \tag{3.3}$$

In addition to economic commodities, industries are also responsible for emitting various residuals into the environment. These are captured by the residual matrix for industries, $\tilde{\mathbf{W}}^{\mathbf{P}}$, with an element $\tilde{w}^{p}_{j,m}$ defining the release of ecological commodity *m* by industry *j*. Environmental commodities used by industries (i.e. raw materials) are also recorded, this time in the matrix, $\tilde{\mathbf{R}}^{\mathbf{P}}$, with an element $\tilde{r}^{p}_{m,j}$ defining the use of environmental commodity *m* by industry *j*.

Next, matrix $\mathbf{P}$ records payments for economic factors of production, by each economic industry. This may include payments to labour, capital, land, and various natural resources[40]. The sum of the row elements of $\mathbf{P}$ gives the vector, $\boldsymbol{\delta}$, detailing the total income paid to each factor *h* ($h \in \{1...\phi\}$), i.e.

$$\delta_h = \sum_j z_{h,j} \,. \tag{3.4}$$

Total household income, ζ, is defined by the equation,

$$\zeta = \sum_h o^f_h + o^g \,, \tag{3.5}$$

where o^f_h describes the value of income from factor *h* received by households and o^g the transfer of income from government to households. Disaggregation of the household and government sectors within a SAM is typically dependent on the intended analytical purpose of the underlying research. Households, for example, are often disaggregated (e.g. by income status or location) into a number of different household categories to assess distributional

[40] Note that factor payments for natural resources (such as coal, oil, natural gas, minerals, fisheries and forestry) are recorded here in monetary units, the corresponding physical flows associated with these payments are captured in the matrix $\tilde{\mathbf{R}}^{\mathbf{p}}$.

impacts, resulting in the need for an additional matrix recording any household-to-household transfers. Similarly, the government sector may be disaggregated into local and central government. In this thesis, households and government are each represented by a single category. In addition to the economic accounts for households, a further vector is specified for households, $\tilde{\mathbf{w}}^{\mathbf{o}}$, which records the direct production of residuals by that sector. Like the industry accounts, the household accounts also contain a vector describing the use of environmental commodities. An element $\tilde{r}_m^o$ of this vector describes the total use of environmental commodity m by households.

The government sector accounts contain a number of different tax vectors (i.e. $\mathbf{x}^{\mathbf{t}}$, $\mathbf{x}^{\mathbf{p}}$ and $\mathbf{x}^{\mathbf{d}}$) and scalars (i.e. x^o, x^g and x^c), capturing the various places within the economic system at which taxes may be levied. Together these taxes, plus any factor payments directly to government, which are also included in vector, $\mathbf{x}^{\mathbf{d}}$, form the total income received by the government sector, η. Thus,

$$\eta = \sum_i x_i^t + \sum_j x_j^p + \sum_h x_h^d + x^o + x^g + x^c . \tag{3.6}$$

Finally, the income component of the capital account is comprised of depreciation, $\mathbf{d}^{\mathbf{f}}$, household savings, s^o, and government savings, s^g.

Having described all accounts for the within-economy components of the framework, as well as the environment-economy interface, the only accounts still requiring explanation are those for the within-environment components. First, matrix $\tilde{\mathbf{B}}$ is the equivalent of the Supply matrix, $\mathbf{V}$, but for the environment rather than the economy. An element $\tilde{b}_{n,m}$ describes the supply of environmental commodity m by environmental process n. Conversely, an element of the environmental Use matrix $\tilde{a}_{m,n}$ describes the use of environmental commodity m by environmental process n. To ensure materials balance within the environmental commodity accounts, a further vector $\tilde{\mathbf{q}}$ is also required, recording the net difference between supply and demand of each environmental commodity. For both the commodity and process accounts, row and column balances hold, thus,

$$\sum_j \tilde{r}_{m,j}^p + \tilde{r}_m^h + \sum_n \tilde{a}_{m,n} + \tilde{q}_m = \sum_j \tilde{w}_{j,m}^p + \tilde{w}_m^h + \sum_n \tilde{b}_{n,m} \tag{3.7}$$

and

$$\sum_m \tilde{b}_{n,m} = \sum_m \tilde{a}_{m,n} \,. \tag{3.8}$$

Measurement Units

An important feature of the above framework is that it is allows for mixed units. A tilde (~) indicates those matrices and vectors that are specified in physical (i.e. mass) terms, while the remaining matrices, vectors and scalars are measured in financial (i.e. monetary) terms. Note also that the original formulation of IO by Leontief was in mixed units.

The commodities and processes that are contained within the environment components of the framework are those that make up the global biogeochemical cycles. As already stated, the analysis is restricted to C, N, P, and S biogeochemical cycles. All commodities that are either inputs to, or outputs from, processes contained within, for example, the C cycle are measured by the mass of C content within the commodities. Similarly, commodities relating to the other cycles are recorded in terms of their relevant N, P or S content, as appropriate. Thus, all matrices and vectors with an environmental commodities dimension can be further partitioned into sub-matrices representing each cycle. To illustrate, the matrix recording the use of environmental raw materials by economic industries, $\tilde{\mathbf{R}}^{\mathrm{p}}$, can be further specified as,

$$\tilde{\mathbf{R}}^{\mathrm{p}} = \begin{bmatrix} \tilde{\mathbf{R}}^{\mathrm{p,C}} \\ \tilde{\mathbf{R}}^{\mathrm{p,N}} \\ \tilde{\mathbf{R}}^{\mathrm{p,P}} \\ \tilde{\mathbf{R}}^{\mathrm{p,S}} \end{bmatrix}, \tag{3.9}$$

where the second superscript denotes the specific element (i.e. C, N, P, and S) content of the commodity measured. Note that some commodities contain more than one element (e.g. plant matter, plankton), and thus are recorded more than once in the list of commodities, but each time measured in their appropriate contributions, i.e. there is no double counting.

The selection of monetary units rather than physical units to record within-economy flows is pragmatic. While there is a severe paucity of information pertaining to within-economy

physical flows, there are a number of national and intra-national statistical agencies collecting readily available financial information on within-economy activities. The use of monetary units for within-economy flows also has some advantages. In the field of IO analysis, it has been noted that an analysis based on a monetary table will produce the same results as an analysis based on a physical table if, for each type of commodity, a uniform price is applicable (refer to, for example, Dietzenbacher *et al*., 2010). In situations where commodity prices are not uniform, PIOTs are often claimed to be superior to monetary IO tables as price influences are removed. Note that even assuming uniform commodity prices, the consistency between the monetary IO table and PIOT is only possible if every monetary flow has some type of equivalent physical flow to which a price (e.g. $/kg, $/joule) can be applied. Nevertheless, the provision of many economic services (e.g. transportation, education, healthcare, legal and other provisional services), involve no significant exchanges of physical goods. Many, if not all, of these services will utilise raw materials and produce residuals either directly or indirectly in embodied terms. In the absence of a physical commodity on which to attach the embodied services, it is not possible to use a PIOT to trace the appropriation of environmental services through production chains. However, the use of financial information better enables the drivers of economic activities to be captured, and the responsibilities and causality for environmental pressures to be identified.

A further argument for the use of monetary units for the within-economy flows is that this facilitates production of a relatively generic framework that can be applied to a range of economic data, either produced in the symmetric form of an IO table or produced as non-square SUTs (refer to Appendix B for further discussion). When dealing with non-square tables there will undoubtedly be examples of true joint production (e.g. wool and lambs for sheep farming, milk and meat for dairy cattle farming), the treatment of which calls for a judgement on how the 'responsibility' for environmental pressures should be allocated (Lenzen *et al*., 2006). In most situations the relative monetary values of joint products will be an appropriate measure for allocating resource use and residual production among commodities, as these values show the relative contribution of each economic commodity to the total incentive to undertake the activity itself. It might also be argued that processes paying a higher price for a particular commodity should indeed be allocated a relatively higher responsibility for the environmental pressures associated with the production of that commodity.

3.4 Dynamic System Framework

As already explained, dynamic models focus more on the processes and behaviours that cause change within a system, than on the structural components that make up a system. Overall, by considering interrelationships across time, dynamic models enable "the derivation of theorems concerning the values of variables, or changes in those values" (Kuenne, 1963, p.14). A dynamic model is therefore suited to investigating questions such as, "What are the implications over the next 50 years of substituting fossil fuels for biofuels or tax regimes aimed at reducing carbon emissions?", or more generally, "What are the potential impacts on the biogeochemical cycles associated with, say, a continuation of current rates of economic growth?"

Dynamic modellers such as Forrester (1971a, 1971b), Ruth and Hannon (1997), Hannon and Ruth (1994, 2001), Deaton and Winebrake (2000), and Sterman (2000) have outlined a number of reasons why dynamic modelling is of value – all of which are relevant to the core aim of furthering sustainability in relation to the biogeochemical cycles:

- *Understanding the complexity of a system without being overwhelmed*. Many systems contain balancing and/or reinforcing feedback loops,[41] time lags, interdependencies and non-linear behaviours. Such complexity quickly overwhelms the unaided human mind, reducing the ability to envisage how a system might behave under change. Developing a dynamic model helps overcome this issue;
- *Generation of new knowledge*. Dynamic models enable exploration and experimentation through creation of simple 'what if' questions, in turn facilitating better understanding of the system including the identification of enablers and inhibitors as well as the behaviour of key processes and causal mechanisms;
- *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; and
- *Assessment of future options*. 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 future actions.

[41] Balancing (i.e. negative) feedback loops counteract an initial change, while reinforcing (i.e. positive) feedback exacerbate an initial change.

Based on these attributes, model building is an indispensable tool for both helping build comprehension and assisting in the selection of alternative actions. Any given model is, however, unlikely to address these two broad goals with equal aptitude. While a relatively broad and simple model is most useful in helping generate a general understanding of system behaviour across a variety of stakeholders, this may be inadequate for selecting among specific policy options where a relatively high degree of confidence in outcomes is required. In these regards, Costanza and Ruth (1998) provide a helpful overview of the modelling process, suggesting that it begins with the simplified, high generality models most suited to initial scoping of problems and consensus building. Once the research agenda is sufficiently defined, the modelling moves towards a more realistic, research stage, typically involving the collection of large amounts of historical data for calibration, testing and uncertainty analysis. Finally, high precision management models are developed, with the aim of considering specific scenarios and management options.[42]

3.4.1 A Brief Overview of Dynamic Modelling Approaches

This thesis adopts System Dynamics as the modelling approach for investigating dynamics of the coupled economic and biogeochemical cycling systems. It is worth noting, however, that other dynamic modelling approaches exist. This section provides a brief overview of System Dynamics and alternative modelling approaches.

Statistical Models

Statistical models use independent variables to describe dependent relationships, obtaining an indication of the relative influence of each of the variables (Bannock *et al*., 1992). Econometrics, including regression analysis, may also be used to predict short-term future trends. Although advances in statistical models now allow for a great variety of model specifications, these models tend to require rich data sets and elaborate specification if they are to deal with multiple system feedbacks and spatial or temporal lags (Sterman, 1991;

[42] Much earlier Meadows (1980) also suggested a three-stage approach to model building for social decision making. At the first stage, where a problem may have never been studied or past studies are incomplete, models are targeted towards general understanding. Although quantitative precision is probably unattainable at this stage, the very process of building such models improves understanding via systematically asking questions and defining new conceptions. At the next stage, models are targeted more towards policy formulation. Broad policy choices are evaluated and compared to identify possible trade-offs or synergies. Then, during the final stage, with a basic policy direction already selected, the concern is generally with addressing a variety of questions concerned with detailed implementation of policies. At this stage, models tend to be highly detailed and accurate and involve the organisation and processing of many pieces of information.

Costanza and Ruth, 1998). Moreover, these models are typically based on observed historical trends and thus may not adequately capture the influence of alternative management schemes, emergent properties, limiting factors or thresholds if these are not represented by historic behaviour.

Optimisation/ Mathematical Programming Models

Optimisation models, including CGE models, may also be applied to study temporal dynamics. Optimisation models tend to breakdown a problem into three conceptual components: an objective to maximise or minimise, the activities or options available to achieve this objective, and any constraints or bounds that must abided (Meadows and Robinson, 2007). Rarely do complex systems, such as an economy or the biogeochemical cycles, however, maximise or minimise a single objective. Moreover, even though multi-objective optimisation may be constructed, these often become intractable in the modelling of complex systems.

Dynamical Systems

Dynamical Systems modelling shares a number of characteristics with Systems Dynamics. In particular, both modelling approaches are well suited to describing the evolution of systems with time-dependent states via mathematical formalism of causal relationships.[43] Recognising that time is continuous, Dynamical Systems modelling relies predominantly on *ordinary* differential equations to simulate such system states over time. Given that many different disciples are interested in the study of time-dependent systems, Dynamical Systems modelling has been employed in a great variety of applications, including applications from biology, chemistry, physics, finance, and industrial applied mathematics. Note, however, that solving mathematical problems comprised of numerous differential equations is often extremely difficult. Hence graphical and numerical solutions, applied either by hand or by computers, are often used to approximate solutions. Even with such techniques available, mathematical complexity remains a core challenge to the more widespread application of the approach for analysis of, and learning about, complex systems.

System Dynamics Models

System Dynamics is often described as a computer-aided modelling approach to policy analysis and design (e.g. Richardson, 2011). It is worth noting, however, that models constructed

[43] *Relationships* are connections that are postulated to exist between different elements of a system. In turn, *elements* are generally visible or measurable system objects or flows. A relationship is deemed to be *causal* if it incorporates some hypothesis about the mechanisms whereby one element directly influences another element (Meadows and Robinson, 2007).

within System Dynamics programming languages are also frequently employed in problems that are not of a strict policy-orientation, for example design and engineering applications. Jay Forrester, at the Massachusetts Institute of Technology, developed System Dynamics in the mid-1950s.[44] At that time, Forrester was interested in understanding the success and failure of corporations. Using General Electric as a case study, he showed, using hand drawn simulations, how employment issues at General Electric were the result of internal structures and not business cycles. In the late 1950s, Forrester and his team of graduate students developed the DYNAMO System Dynamics computer language. This was followed by publication of *Industrial Dynamics* (1961), *Urban Dynamics* (1969), and *World Dynamics* (1971). In 1972, following on from the notoriety received by *World Dynamics*, the Club of Rome initiated the famous *Limits to Growth* (Meadows *et al*., 1972) study.

The Systems Dynamics approach relies specifically on finite differential equations to approximate solutions for differential equations along a path of successive 'time-steps'. Although this results in some loss of information and precision, it significantly widens the scope of modelling exercises, enabling very complex systems to be represented within a computer simulation model, even by practitioners with no advanced mathematical training. Two popular graphical programming languages are now available for facilitating the construction of System Dynamics models, STELLA® and Vensim®. Both contain visual display and input and output features that enable users to easily grasp model structures, interactively run models and review results. As noted by Costanza and Ruth (1998), given the relative ease of use, these programmes constitute powerful tools for enquiry into the nature and dynamics of complex systems. A number of well-known practitioners advocate that System Dynamics models should be relatively simple and aggregate, and used primarily for the general understanding or policy-design stages of decision-making (see, for example, Meadows and Robinson (2007, p.38)). Nevertheless, array capabilities within the programming languages now allow for the modelling of systems that are highly disaggregate, for example, consisting of many different actors or spatial locations.

[44] Forrester was also a pioneer of digital computing. During the 1940s he led the Whirlwind project, a Cold War vacuum tube computer, which in a later form was the basis for the United States Air Force air defence system until the mid-1970s. During this time, he also created the 'Multi-coordinate Digital Information Storage Device' a key predecessor of today's computer Random Access Memory (RAM). He is currently Professor Emeritus of the Sloan School of Management at the Massachusetts Institute of Technology.

3.4.2 Core Elements of the System Dynamics Approach

Aspects of the System Dynamics approach are presented and employed in the development of the DGES (Chapter 7), DGBCM (Chapter 8), and Ecocycle (Chapter 9) models. As an introduction, however, Table 3.1 provides a brief overview of some of the core concepts and techniques of this approach.[45] Like any model of a system, a System Dynamics model, is a simplification of the system under consideration – in the end, the only full representation of a system is itself.

Table 3.1 Principal Concepts and Techniques of System Dynamics

Concept/technique	Description
Causal loop modelling	A type of diagram used to represent the general pattern of elements and interrelationships (i.e. structure) of a system. Causal associations between two elements, or variables, are depicted by arrows. The variable at the tail of the arrow causes change to the variable at the head of the arrow. Causal loop modelling is often undertaken prior to the construction of a simulation to help clarify core components to include within the simulation model.
Feedback loops	Systems are comprised of closed chains of causal relationships. This means that the effects of a cause (e.g. a change in one variable) can be traced through a set of related variables back the the original cause. In general feedback loops are positive (reinforcing) or negative (counteracting or self-regulating).
Stocks	Stocks are quantities within a simulation model that accumulate over time. A stock therefore describes the condition of a system, and would continue to exist even if all relevant inflows and outflows to that stock ceased to exist.
Flows	A flow is the change to a stock occurring over a defined period of time. For example the number of births adding to a population stock during one year.
Converters	Converters are auxiliary variables employed in functions that help to define either other converters or flows.

[45] Although many of these concepts are employed in other types of modelling, they deserve special recognition for constituting the core set of concepts within System Dynamics.

Part II: Static Analysis

"Indicators arise from values (we measure what we care about), and they create values (we care about what we measure)…[C]hanging indicators can be one of the most powerful and at the same time one of the easiest ways of making system changes – it does not require firing people, ripping up physical structures, inventing new technologies, or enforcing new regulations. It only requires delivering new information to new places."

Meadows, 1998, pp.viii, 5

Chapter 4

Material Flow Accounts for the Global Economy

4.1 Introduction

This chapter is the first of two chapters describing the development of mass flow accounts in accordance with the ESAM system framework set out in Chapter 3 (see Figure. 3.4).[46] This chapter focuses specifically on the derivation of mass flow accounts, which describe the quantities of C, N, P and S extracted from the environment by the economy ($\tilde{\mathbf{R}}^{\mathbf{p}}$ and $\tilde{\mathbf{r}}^{\mathbf{o}}$ of the ESAM), and the quantities of mass then released back into the environment ($\tilde{\mathbf{W}}^{\mathbf{o}}$ and $\tilde{\mathbf{w}}^{\mathbf{o}}$ of the ESAM). Not only do these accounts provide baseline information on the role of the global economy in biogeochemical cycling, from which the ecotime indicators are derived (Chapter 6), they also constitute a valuable input to the construction of the Ecocycle environment-economy dynamic model (Chapter 9).

Despite the importance of understanding and monitoring humanity's reliance and impact on environmental systems, including by way of recording and monitoring mass and/or energy flows,[47] there is an overwhelming dearth of this type of information available from national statistical agencies and other data collection organisations. As a result, the compilation of the accounts described in this chapter has been an extremely onerous task, involving collation of a myriad of disparate and ad hoc information sources, and application of a variety of bottom-up and top-down estimation methods. It would appear that the MFA accounts produced in this thesis are now the most detailed and comprehensive information available on C, N, P, and S flows for the global economic system.

In compiling the mass flow accounts, reference has been made particularly to the concepts and definitions developed under MFA. For this reason, the accounts are termed specifically

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[46] Note that the financial flows set out in that framework (i.e. the within-economy flows) are taken directly from the Global Trade Analysis Project (GTAP 7.0) database.

[47] As set out in Chapter 2, decoupling mass and energy throughput from economic output is an important goal for progressing sustainability. Without the availability of basic accounts, it would be difficult, perhaps impossible, to understand how society might further this goal and monitor progress. Various indicators can also be derived from accounts such as those described in this chapter. Chapter 6, for example, develops a set of 'Ecotime'-based accounts, but various other types of indicators might also be produced. As further noted in Chapter 2, the process of measuring, recording, and producing indicators is, in itself, a tool for change and learning.

'Material Flow Accounts for the Global Economy'. MFA is a physical accounting approach that adheres to the Mass Balance Principle and is concerned particularly with measuring and recording mass flowing into a system, the stock changes within that system, and the resulting output flows to other systems. MFA allows for application of internationally recognised classification systems that enable it to be directly linked to the United Nations 1993 System of National Accounts. This, in turn, enables MFA to be applied at various scales and for various types of systems, e.g. firms, aggregated sectors, city-region economies, national economies and for the globe.

Although many MFA studies measure *total* mass inputs/outputs of a system, a number have also concentrated on measuring specific materials or elements. Examples include Maag *et al*. (1997) for mercury, Graedel *et al*. (2002) for copper, Antikainen *et al*. (2004) for N and P through the Finland forestry industry, and Cordell *et al*. (2009) for P flows through the global food production and consumption system. A number of other studies, although not termed MFA, have developed similar mass flow accounts for biogeochemical flows, including the European Science Foundation's Nitrogen in Europe Programme (Sutton *et al*., 2011a) and the C, N and P supply and use tables by Fujimori and Matsuoka (2007). An important point to note about the accounts described in this chapter is that the biogeochemical exchanges between the environment and economy are described by not only by the economic sectors responsible for the exchange, but also by the environmental commodity stocks from which inputs are sourced or outputs are destined. Definition of the relevant environmental commodity stocks is particularly important in enabling seamless integration between the ESAM's environment and economy components.

The remaining sections of this chapter begin (Section 4.2) with a short introduction to key definitions and classifications from MFA. The MFA classification system provides a convenient typology that ensures all mass flows to and from the economic system are covered by the accounts. The bulk of the chapter (Section 4.3) is devoted to describing the various methods and datasets relied on for compilation of the accounts. The final part of the chapter (Section 4.4) provides an overall summary of the MFA accounts for each of C, N, P and S, including a summary diagram for each element. Note that the summary diagrams are produced in the 'Sankey' format,[48] and in their own right constitute a fascinating description of the 'industrial

[48] Sankey diagrams are a type of flow diagram in which the width of arrows is used to indicate the relative magnitude of each flow. They diagrams take their name from Matthew H. P. R. Sankey, who used this type of diagram to show the energy efficiency of a steam engine (Sankey, 1898).

metabolism' of the global economic system. A more-detailed version of the MFA accounts is available on the accompanying CD-ROM (see also Appendix H of this thesis).

4.2 Definitions and Classifications

To help determine the environment-economy exchanges, all material flows in the ESAM are coded to the 58 sectors of the Global Trade Analysis Project (GTAP 7.0) database,[49,50] which concordances with the internationally recognised CPC and ISIC systems. A full list of the GTAP sectors along with their mapping to the CPC and ISIC systems is provided in Table C.1 of Appendix C. Note that this table also includes a consumer sector termed 'households'. All material flows produced outside economic industries are allocated to this sector, thus making it one of the most important sectors within the MFA accounts.[51]

Like many other examples of MFA, this chapter does not focus on describing within-economy mass flows, i.e. between industries or from industries to consumers. As an exception, separate accounts for waste production and waste treatment are included. The development of a full set of within economy mass flows (i.e. as per a PIOT) is beyond the scope of this thesis. The input and output flows included in this chapter account for 6 different types of human processes (i.e. waste production, residual production, waste treatment, non-processed flows, waste recycling/use, and direct material inputs) by 58 different sectors by 134 C, N, P, and S environmental commodities stocks. Despite the sparse nature of this matrix (348 rows by 134 columns, but only 4,596 non-blank cells) it is not possible to present this as a hardcopy Table in this thesis. It is instead presented in the accompanying CD-ROM under the Chapter 4 directory.

As the focus of this chapter is on quantifying material flows between the environment and the economy, the chosen boundary defining the economy is important (refer to Figure 3.2 of

[49] A publicly available global database utilised by many economic practitioners particularly for the purposes of applied General Equilibrium analysis. Refer to www.gtap.agecon.purdue.edu.

[50] A key weakness of GTAP 7.0 is that is it assumes only one homogeneous commodity output per industry, ignoring that industries often produce more than one product e.g. a sheep farm may produce sheep for meat processing and wool for textile manufacture. It is worth noting that recently Timmer (2012) produced prototype World IO Table from SUTs. Potentially these SUTs could be used to replace the GTAP 7.0 data, thus, allowing joint production to be addressed. Timmer (2012) also provides compatible environmental accounts for energy use, CO_2 emissions, and emissions to air at an industry level that can also potentially replace similar data from GTAP 7.0.

[51] To maintain consistency with Chapter 3, the term 'sector' is used to refer to any group of activities that include both producers (industries) and consumers (households).

Chapter 3). Substances extracted from the environment are frequently separated into two major categories: direct material inputs and non-processed material flows (Adriaanse *et al*., 1997; Eurostat, 2001). The Eurostat (2001, p.27) MFA manual defines direct material inputs as "all solid, liquid and gaseous materials that enter the economy for further use in production or consumption processes". In this thesis, these are classified into five principal groups: biomass (extracted through agriculture, forestry, fishing, etc.), materials for biomass production (where primary production processes occur inside the economy), minerals, fossil fuels, and unreactive N (for use in industrial N-fixation).

Non-processed material flows are sometimes separated into two subcomponents comprising 'unused extraction' on the input or extraction side, and 'disposal of unused extraction' on the output or disposal side (Eurostat, 2001). Unused extraction flows have been defined by Eurostat (2001, p.21) as "materials extracted or otherwise moved on purpose and by means of technology which are not fit or intended for use" or "materials that never enter the economic system and thus can be described as physical market externalities". In a way, non-processed material flows can be viewed as akin to concurrent material input and residual flows, but omitting any processing of these materials within the economy. Examples include mining overburden, soil excavated and moved during construction, fish by-catch, and wood harvesting losses. In this thesis the concept of non-processed material flows is extended to capture some other important biogeochemical processes arising directly out of human activities, namely (1) organic matter combustion during human-induced vegetation fires, (2) biological N-fixation within agricultural systems, (3) N-fixation within internal combustion engines, and (4) emissions from rice agriculture. Inclusion of (1) and (4) ensures that atmospheric emissions attributed to anthropogenic processes are consistent with the IPCC's methodological guide (IPCC, 2006). Similarly, N-fixation covered by (2) and (3) is typically attributed to the economy (Gruber and Galloway, 2008; Canfield *et al*., 2010).

Eurostat (2001) define outputs to the environment as all materials released to air, land or water, so that human control is lost over the location and composition of the materials released. As noted in Chapter 3, the term 'residual' is used to describe the commodities released to air and land, with the later including freshwater. Residuals discharged to land include a number of flows often referred to as 'dissipative uses', for example, fertilisers and materials spread on fields.

4.3 Derivation of Material Flow Accounts

4.3.1 Direct Material Inputs

Biomass Extraction

The ESAM covers three major categories of biomass extraction: grazed consumption of biomass by domestic animals, wood and timber removals, and global fish harvests. Omitted are a number of smaller extraction flows e.g. honey, mushrooms, berries, and herbs.

Starting with grazed consumption of biomass, international agricultural databases such as those published by the Food and Agricultural Organisation (FAO) contain data only on *market* feed and fodder crops fed to livestock. Comprehensive estimates of biomass grazed by livestock or otherwise mowed for livestock feed are unavailable. Krausmann *et al*. (2008) calculate the 'grazing gap' required to sustain the world's livestock, in addition to market crops, as 3.84 Pg of dry matter for the year 2000. Accounting for increases in global livestock numbers, and assuming that grazed biomass has the same stoichiometry as terrestrial vegetation[52] produces total flows of 2.00 Pg C, 22.4 Tg N, 6.5 Tg P and 20.9 Tg S. These flows are apportioned among different livestock types, and GTAP sectors,[53,54] based on default feed intake ratios (kg/head/day) reported by the IPCC (1996), accounting for the proportion of each livestock type reared in confinement and thus not involved in grazing (Smil, 1999).

Krausmann *et al*. (2008) also provide an estimate of the total wood harvest in 2000 as 1.94 Pg dry matter. Their calculation is based on harvest volumes reported in the Temperate and Boreal Forest Resource Assessment 2000 database (United Nations, 2000) and FAO statistics (FAO, 2005), along with adjustments for unreported bark volumes. In some parts of the world, significant quantities of woody biomass are gathered from not only forests and groves, but also bushes, rubber plantations, roadside and backyard trees to support household fuel demands (Smil, 2008). A household wood extraction flow of 0.45 Pg C is adopted in the ESAM, derived from the difference between the FAO wood fuel estimates and the total wood required to satisfy residential wood fuel demands (Fernades *et al*. 2007). Overall, the total wood removal flows are calculated as 1.23 Pg C, 13.8 Tg N, 4.0 Tg P, and 12.9 Tg S. Out of

[52] Refer to Section 5.4.1.

[53] All flow values in this chapter, as per Chapter 5, are for the 2004 calendar year unless otherwise specified.

[54] Refer to Table 5.6 for a concordance between livestock types and GTAP sectors.

these flows, 59 percent is allocated to the household sector and the remainder to the forestry industry (Fernades *et al*. 2007).

Although human fish harvests have had significant impacts on marine ecosystems with, for example, at least a quarter of global commercial marine stocks estimated to be either overexploited or completely depleted (FAO, 2005), the actual input of biomass to the economy associated with fish harvests is small when compared with other flows. Fish, crustacean, mollusc and so on capture in marine fishing areas is reported by the FAO (2008) as 83.8 Tg, with an additional 16.7 Tg produced through aquaculture production. These values translate to a total of 11.2 Tg C, assuming that C makes up around one-ninth of the total wet-weight of fish (Strathmann, 1967; Pauly and Christensen, 1995). Note, however, that because harvested fish constitute a major feed input to aquaculture systems (Hasan and Halwart, 2009), simply adding the marine capture and aquaculture flows together will result in double counting of material inputs to the economy.[55] The ESAM thus includes a 'net' fish harvest flow, calculated by subtracting the estimated mass of fish used as inputs to marine aquaculture (Tacon and Hasan, 2007), from the total mass of fish produced from marine wild harvests plus aquaculture. The derived C flow of 10.5 Tg is then multiplied by the stoichiometry for marine consumers[56], to calculate the associated flows of N, P and S.

Biomass Production

In the ESAM, crop production is a process residing within the economy. The total element content of crops is calculated as 1,990 Tg C, 71,600 Gg N, 2,980 Gg P and 11,430 Gg S (Table 5.1). These values are calculated via a bottom-up approach. In brief, this involved extracting estimates of total global production (measured in t) for some 200 different crop types from the FAO Food and Agricultural Commodities Production database,[57] then multiplying the production values for each crop by dry matter content ratios, and subsequently element-to-dry matter content ratios, for each of C, N, P and S elements. The relevant ratios are derived from a variety of values reported in the literature (Mishra and Shukla, 1986; IPCC, 1996; Smil, 1999; Gunderson *et al*., 2000; Vleeshouwers and Verhagen, 2002; Fujimori and Matsuoka, 2007). Unfortunately, there is a paucity of information on the S content of crops. To generate

[55] Ideally, aquaculture would be classified as an economic stock, analogous to domestic livestock. Data limitations have however precluded this approach.
[56] Refer to Section 5.5.2.
[57] http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567, accessed 8 Jan 2011.

an approximation of the S needed for crop production, the S:P ratio for terrestrial vegetation[58] is applied. Table C.2 of Appendix C maps the FAO crops to the GTAP sectors.

The FAO data do not cover aboveground crop residuals such as straw, stover, and leaves. To estimate the flow of crop residuals, the FAO production data for each crop are multiplied by a residual-to-crop ratio (IPCC, 1996; Smil, 1999; Yevich and Logan, 2003; Fujimori and Matsuoka, 2007; Krausmann *et al*., 2008). Once again, the resulting estimates must be multiplied by dry matter content ratios, followed by element-to-dry matter composition ratios, to derive C, N, P, and S content estimates.

Although less apparent, crop production generates significant quantities of belowground residuals, primarily roots left during harvests. This flow, along with crop losses to animal pests, is grouped into the non-processed material flows category, but is outlined in this section for convenience. These residuals are estimated to be 608.7 Tg C (Krausmann *et al*., 2008). It is assumed that belowground residuals exhibit the same element stoichiometry as that of terrestrial vegetation[59]. The belowground residual flow for each element is then disaggregated among GTAP sectors according to each sector's contribution to crop production and aboveground residual production.

Before crop harvesting, a relatively significant quantity of plant biomass may be consumed or destroyed by agricultural pests. Although this matter is lost before it is can be applied in economic activities, these material flows are a by-product of agriculture, and hence treated as a non-processed material flow. Oerke (2006) provides estimates of the loss in yield of wheat, rice, maize, potatoes, soybeans and cotton crops for the period 2001–03. Total losses from animal pests alone are estimated to range between 11.0 percent of actual yield for wheat, to 24.1 percent for rice. It is assumed that the amount of plant biomass consumed by animal pests is 15 percent of the total C biomass produced in crops and crop residuals.

[58] Refer to Section 5.4.1.
[59] Refer to Section 5.4.1.

Table 4.1 Biogeochemical Species Required for Crop Production, 2004

GTAP Code	GTAP Name	Direct Material Inputs		Non-Processed Materials		Total
		Crops	Aboveground residuals	Belowground residuals	Crops lost to animal pests	
Carbon dioxide (Tg C)						
1	Paddy rice	222	310	86	128	746
2	Wheat	270	351	89	68	779
3	Other grains	301	592	132	125	1,150
4	Vegetables, fruits	189	306	74	73	641
5	Oil seeds	245	223	68	56	592
6	Sugar cane	214	167	58	66	505
7	Plant-based fibers	18	36	8	9	71
8	Other crops	532	98	94	93	817
	Sub-total	1,991	2,083	609	618	5,301
Soil inorganic nitrogen (Gg N)						
1	Paddy rice	9,610	4,490	2,270	3,400	19,770
2	Wheat	10,000	4,340	2,060	1,580	17,980
3	Other grains	11,600	7,620	2,840	2,680	24,730
4	Vegetables, fruits	10,630	4,840	2,300	2,280	20,050
5	Oil seeds	3,680	2,540	900	740	7,870
6	Sugar cane	2,200	2,560	720	820	6,310
7	Plant-based fibers	270	410	100	120	890
8	Other crops	23,620	1,350	3,710	3,690	32,360
	Sub-total	71,610	28,150	14,900	15,310	129,960
Soil inorganic phosphorus (Gg P)						
1	Paddy rice	430	750	190	280	1,650
2	Wheat	280	720	140	110	1,260
3	Other grains	610	1,270	280	260	2,420
4	Vegetables, fruits	330	660	150	150	1,280
5	Oil seeds	250	380	90	80	800
6	Sugar cane	300	380	100	120	900
7	Plant-based fibers	20	60	10	10	110
8	Other crops	760	200	140	140	1,250
	Sub-total	2,980	4,420	1,100	1,150	9,670
Soil inorganic sulphur (Gg S)						
1	Paddy rice	1,370	2,400	610	910	5,290
2	Wheat	1,430	2,320	540	410	4,700
3	Other grains	1,660	4,070	850	800	7,380
4	Vegetables, fruits	1,270	2,120	500	500	4,400
5	Oil seeds	1,080	1,220	330	270	2,910
6	Sugar cane	1,270	1,230	380	430	3,320
7	Plant-based fibers	80	200	40	50	360
8	Other crops	3,270	650	580	580	5,080
	Sub-total	11,430	14,210	3,830	3,950	33,440

Minerals Extraction

Although humans extract a vast array of minerals from the lithosphere, this thesis is concerned only with those containing appreciable quantities of C, N, P, and S (Table 4.2). In terms of C, $CaCO_3$ minerals, including limestone, marble, chalk and dolomite, are by far the most important, with demands for use both in industrial processes (e.g. fertiliser manufacture) and in construction (e.g. aggregates/cement). Despite the economic importance of these minerals, only limited data are available on worldwide demand. While information does exist on bulk construction minerals in the UN Industrial Commodity Statistics and USGS databases, problems of incomplete global coverage, and the reporting of $CaCO_3$ minerals in conjunction with other minerals, exist. Additionally, of the mass flows recorded in the literature (Behrens *et al*., 2007; Schandl and Eisenmenger, 2006; Steinberger, 2010), it is difficult to determine the likely $CaCO_3$ content. A pragmatic bottom-up approach is therefore applied. This involves identifying industrial C residuals that are likely to stem from the use of $CaCO_3$ as a feedstock, estimating the mass of $CaCO_3$ required for these industrial processes, and then summing over all the industrial processes. No attempt is made to quantify the mass of limestone used directly as a construction material. Keeping with the Mass Balance Principle, thus, limestone construction wastes must be excluded from the calculation of C waste and residual flows.[60]

The Emission Database for Global Atmospheric Research (EDGAR) reports emissions from cement, 245 Tg C, and lime, 53 Tg C, manufacture. The database also reports an emission flow of 14 Tg C associated with other mineral production. Although a proportion of the latter emissions will originate from fossil fuel feedstocks, it is likely that soda ash production and use, relying on $CaCO_3$ as a feedstock, is one source (IPCC, 1996). The US Environmental Protection Authority (USEPA) reports US emissions from soda ash production and use, as 1 Tg C yr^{-1} during the early 2000s, and estimates that this is around one-quarter of the global total (USEPA, 2010). Other principal industrial uses of $CaCO_3$ involve limestone and dolomite use in metal manufacturing, glass making and flue gas desulphurisation. Using emission ratios derived from the US GHG inventory (USEPA, 2010), global emissions from these sources are estimated at just over 10 Tg C. Summing all these categories together produces a total global demand for $CaCO_3$ in industrial processes of at least 314 Tg C. This demand is incorporated in the ESAM via an extraction flow from the carbonate minerals stock.

[60] It is worth noting that limestone is a relatively benign biogeochemical species, subject to slow rates of decomposition.

Minerals containing PO_4^{3-} are also mined from the lithosphere, primarily for use as fertilisers. There is a variety of other minor industrial uses for P, including in the production of food and beverages, cleaning products, and flame-retardants, for treatment of potable water, and in processing of ceramics. The USGS (2004) estimates PO_4^{3-} rock production at 19.8 Tg P.

Table 4.2 Summary of Direct Material Inputs of C, N, P and S to the Economy (Excluding Biomass Extraction and Production), 2004

Process	Source Stock	Flux Tg/Gg[1]	GTAP Code
Minerals			
Quarrying of limestone (excl. cons. materials)	Lithosphere carbonate minerals (C)	314	18
Phosphorus mining	Lithosphere other crustal P (P)	19,760	18
Sulphur mining (excluding gypsum)	Lithosphere other crustal S (S)	37,600	16-18
Fossil fuels (excluding fugitive emissions)			
Coal extraction	Lithosphere coal (C)	3,162	15
	Lithosphere coal (N)	54,310	15
	Lithosphere coal (P)	12,560	15
	Lithosphere coal (S)	64,260	15
Petroleum extraction	Lithosphere petroleum (C)	3,098	16
	Lithosphere natural gas (C)	308	16
	Lithosphere petroleum (N)	12,290	16
	Lithosphere petroleum (S)	64,130	16
Natural gas extraction	Lithosphere natural gas (C)	1,657	17
Other			
Industrial nitrogen fixation	Atmosphere dinitrogen (N)	128,180	33

Notes: 1. C flows measured in Tg; N, P and S flows measured in Gg.

More than 90 percent of mined S is used in the production of sulphuric acid, principally for fertiliser production (Brimblecombe, 2005). Smaller amounts of S are used in the manufacture of gunpowder, insecticides, fungicides, medicines, wood products and paper products. This S is obtained directly from the lithosphere in the form of elemental S, from sulfide (pyrite) minerals, but also as a by-product from metal ore and natural gas extraction and processing. The USGS (2006) reports total global production of industrial S to be 32,100 Gg. This does not include S extracted from the lithosphere, but unable to be captured for industrial use. Of particular importance are gaseous emissions (primarily SO_2) from metal production estimated

at 5,460 Gg S. Adding these values together produces an estimated S extraction flow of at least 37,600 Gg.[61]

Fossil Fuel Extraction

The rate at which humans extract C from the lithosphere in fossil fuels is almost equal in magnitude to C extraction in biomass. The US Energy Information Administration reports total world production of coal as 6,223 million short tons for 2004.[62] This equates to some 3,160 Tg C, based on the quantities of C emissions released during combustion (Marland *et al*., 2007), and accounting for the use of coal as a feedstock in other industrial processes. A coal mass ratio of 49.20C:0.85N:0.20P:1S is used to estimate the other element flows associated with coal extraction (White *et al*., 1984; Vorres, 1989; Smith *et al*., 1994; Mastalerz *et al*., 2003; Kabe *et al*., 2004; Higman and van der Burgt, 2008). It also accounts for the relative contribution of different types of coal (anthracite, bituminous and lignite) within total production.

Production of crude oil, including condensate, is reported as 72.5 million barrels per day,[63] which translates to a total extraction of around 3.62 Pg. The mass content of oil is estimated to be 85.5 percent C, 0.3 percent N and 1.8 percent S (Hyne, 1991). Referring again to the US Energy Information Administration datasets, production of dry natural gas is estimated as 97,000 billion cubic feet. The organisation further reports 7.5 million barrels per day of petroleum produced from natural gas plant liquids. Assuming that dry natural gas has an average C mass content of 76 percent, and 83 percent for natural gas plant liquids (Ryder and Buruss, 2003), the total mass of C extracted in natural gas for petroleum and natural gas production is 2,010 Tg.

Industrial N fixation

Industrial N-fixation refers to a group of processes that enable dinitrogen to combine chemically with other elements to form reactive N compounds, such as NH_3, NO_3^-, or nitrites. The Haber-Bosch process, first commercialised in 1913, is by far the most important industrial form of N-fixation. It involves heating N and hydrogen under very high temperature and

[61] The ESAM excludes the mining of gypsum minerals. While some information exists (USGS, 2006), there are difficulties in determining S content. Even more problematic is accounting for S disposed of in waste flows. Gypsum is primarily used for the manufacture of wallboard and plaster products and, thus, the S wastes are predominantly in construction and demolition materials. A severe paucity of information exists with regard to these wastes.

[62] http://tonto.eia.doe/gov/, accessed 5 Apr 2011.

[63] http://tonto.eia.doe/gov/, accessed 5 Apr 2011.

pressure along with a chemical catalyst thus producing synthetic NH_3. Around four-fifths of the reactive N formed from this process is used for fertiliser manufacture (including as a feedstock for urea and for various nitrates, SO_4^{2-} and PO_4^{3-}), and the rest for various other industrial processes such as production of explosives, dyes and fibres (Domene and Ayres, 2001). Estimates of the total quantity of N fixed through the Haber-Bosch process vary quite substantially in the literature. For the 1990s, the global rate has been reported at around 100 Tg N (Gruber and Galloway, 2008; Smil, 2002), while a more recent source reports a rate of around 130 Tg N for 2008 (Canfield *et al*., 2010). The ESAM adopts a rate of 128 Tg N.

4.3.2 Waste Generation

Four primary categories of wastes are covered by the ESAM: livestock excrement, crop residuals (refer to Section 4.3.1), solid wastes and wastewater. The solid wastes category is further broken down into eight sub-categories: (1) paper and cardboard, (2) textiles, (3) vegetable and animal, (4) rubber and leather, (5) plastics, (6) petroleum products and solvents, (7) phosphogypsum and other industrial S wastes, and (8) coal ash P.

Livestock excrement

Element flows in livestock excrement are calculated separately for 16 different livestock types (Table 5.6). Overall, by multiplying FAO livestock population data[64] by estimated manure production rates (Smil, 1999; Fujimori and Matsuoka, 2007), it is calculated that some 2.48 Pg of excrement was produced. Cattle alone are responsible for 60 percent of this total, with the next most important sources being buffaloes (8 percent) and pigs (8 percent). Applying N and P content ratios (Smil, 1999; Fujimori and Matsuoka, 2007), the total flows associated with excrement production are 98,000 Gg N and 4,570 Gg P. C flows are separately estimated as 617 Tg, based on data provided by Prairie and Duarte (2007), while S slows are approximated by the stoichiometry of zoomass.[65] Importantly, only excrement produced by animals in confinement is added to the waste accounts. The remaining quantities of excrement, which are likely to be deposited onto fields, are treated as a residual flow from the economy directly to the litter/detritus stock.

[64] http://faostat.fao.org/site/573/DesktopDefault.aspx?PageID=573#ancor, accessed 17 Oct 2012.
[65] Refer to Section 5.4.2.

Municipal Solid Waste

Solid waste generation rates and composition varies across the world. Unfortunately, only a small number of countries have comprehensive waste data covering different types of wastes and treatment methods. To estimate global solid waste production for sub-categories (1) to (6) above, reference is made to the region-specific default parameters specified in the IPCC's guidelines for national GHG inventories (IPCC, 2006). Calculations based on these default values are undertaken at the level of individual countries, and then aggregated to provide a global total. Actual data from available national GHG inventories and other literature sources (World Bank, 2005; Phuntsho *et al.*, 2010; Dhokhikah and Trihadiningrum, 2012) are substituted into the calculations as appropriate.

Unfortunately, the IPCC guidelines do not provide a method for estimating Municipal Solid Waste (MSW) production by rural populations within developing countries.[66] While these populations may practice dispersed types of waste disposal with high levels of recycling, they are no doubt still responsible for significant wastes. With no information available on the magnitude and composition of these wastes, this thesis includes only estimates of waste originating from plant and animal materials i.e. biogenic wastes. For each developing country, the quantity of biogenic waste produced per capita in rural areas is simply set equivalent to the per capita rate of vegetable and animal waste production by the country's urban population. The total waste estimate is estimated at 265 Tg C.

Very little information is available on the likely element content by solid waste type. IPCC guidelines, however, require reporting countries to track the degradable organic C (DOC) and fossil organic C of waste, and provide a set of default values for DOC, fossil C, and total C content for wastes of different types. Applying these default values, it is estimated that the C flow contained within MSW is around 440 Tg (Table 5.3). Paper and cardboard wastes contribute around 35 percent of this total.

The N and S flows associated with paper, vegetable, animal, rubber, and leather wastes are determined from the relevant C flows by applying stoichiometric ratios for these materials as taken from Chandrappa and Das (2012). The P content of vegetable and animal wastes, however, is approximated from the average C:P content of food crops, while the N, S and P

[66] Countries are only required to record emissions of non-CO_2 species produced from decay of biogenic material or fossil organic C. It is implicitly assumed that rural waste is comprised primarily of biogenic materials and decays primarily to CO_2.

flows for wood waste are estimated from the stoichiometry of terrestrial vegetation.[67] Finally, a stoichiometry for textile wastes is estimated by taking the chemical composition of various textile yarns (including nylon, polyester/plastic, cotton, wool, silk), and then calculating the likely contribution of these yarns to total textile production, based on production data from the UN Industrial Commodity Statistics Database.[68]

[67] Refer to Section 5.4.1.
[68] http://data.un.org/, accessed 8 Feb 2011.

Table 4.3 Composition of Global Solid Wastes and Allocation to Global Trade Analysis Project Sectors Responsible for Generation, 2004

Waste Type	C	N	P	S	GTAP Code	Sector Disaggregation Scalar[2,3]
	Tg	Gg	Gg	Gg		
Municipal solid wastes						
Paper/cardboard	154	1,050		700	1-56, 100	Sectors 1-56: $(indswfact^{w}_{j} \times GTAPoutput_{j}) / (\text{sum}_{j}(indswfact^{w}_{j} \times GTAPoutput_{j}) + hhldswfact^{w} \times pop)$ Sector 100: $(hhldswfact^{w} \times pop) / (\text{sum}_{j}(indswfact^{w}_{j} \times GTAPoutput_{j}) + hhldswfact^{w} \times pop)$
Textiles	11	340	0	10	47-56, 100	
Vegetable and animal[1]	77	4,160	430	640	47-56, 100	
Wood	47	530	150	490	1-29, 32-44, 47-56, 100	
Rubber/ leather	6	980			47-56, 100	
Plastics	140				1-56, 100	
Petroleum products/ solvents	6				51-56, 100	
Industrial solid waste						
Paper/cardboard	6	40		30	31	N/A
Textiles	8	250	0	0	1-44, 46	
Vegetable and animal	18	970	100	150	19-26	
Wood	32	360	100	330	46	
Rubber/ leather	17	290		10	1-44, 46	
Petroleum products/ solvents	13				1-44, 46-50	
Phosphogypsum & other S waste				38,900	32,33	
Other						
Coal ash			12,560		1-56, 100	$cdGTAPcp_{j}/totalcdGTAPcp$

Notes: 1. Excludes estimates for rural developing populations. 2. $indswfact^{w}_{j}$ = sector j waste generation factor for waste type w (g waste/US$ output); $GTAPoutput_{j}$ = total output by sector j from the GTAP 7.0 database (US$); $hhldswfact^{w}$ = household waste generation factor for waste type w (g waste/capita); pop = total world population; $cdGTAPcp_{j}$ = mass of C in emissions from coal products by sector j from GTAP Energy CO_2 accounts; $totalcdGTAPcp$ = total mass of C in emissions from coal products from GTAP Energy CO_2 accounts. 3. The waste generation factors $indswfact^{w}_{j}$ and $hhldswfact^{w}$ are generated from the European Commission's waste generation statistics and economic output data for EU countries from the GTAP 7.0 database.

Industrial Solid Waste

Industrial solid waste (ISW) generation and composition varies significantly between countries, depending on the types of industries, industrial processes and technologies employed. The IPCC guidelines do not contain a set of default production and composition parameters for use in calculating ISW accounts. Countries with no national data are encouraged to use data from like countries. In this thesis, European Commission waste generation and treatment statistics[69] are used as a proxy for the likely production rates (tonnes per US$ million) for waste types (1)–(6) by industry. This comprehensive waste dataset records waste production by both type of waste and generating sector. Note that the methods used to estimate the C, N, P and S composition of these wastes are the same as those employed for MSW. Table 5.3 provides a summary of the estimated element flows.

Based on an analysis of S materials flows within the US (Ober, 2002), inorganic S wastes are mainly generated in the form of phosphogypsum (synthetic gypsum) produced during PO_4^{3-} fertiliser production and in petroleum refining. Sulphuric acid is the major feedstock for these industrial processes. Ober (2002) estimates consumption of sulphuric acid in US PO_4^{3-} fertiliser production at just over 7 Tg S for 2000. This value is scaled to a global estimate for 2004, using world PO_4^{3-} fertiliser production statistics,[70] while also accounting for differences in fertiliser types and quantity of sulphuric acid required (Ober, 2002). Phosphogypsum waste production from fertiliser manufacturing is estimated to be 20 Tg S. The USGS (2006) estimates consumption of S within the US for petroleum refining as 4 Tg. This is scaled to a global estimate of 19 Tg, based on petroleum product statistics contained within the United Nations Industrial Commodity Statistics Database[71]. A very small proportion is already accounted for in the wastewater estimates for petroleum manufacturing. All remaining inorganic S emitted from petroleum manufacturing as a solid waste is deposited to landfills.

Coal Ash P

This is a special category of solid waste that does not fit neatly into either the MSW or ISW categories. Although the majority of P contained within coal is expected to be found in bottom ash following combustion (Szpunar, 1992), some P is also likely to be emitted as fly ash that eventually settles onto the land or ocean. A proportion of coal P is also likely to end up in economic products, e.g. P absorbed into metals during steel manufacture. As there is limited

[69] http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/, accessed 8 Mar 2011.
[70] http://www.fertilizer.org/ifa/HomePage/STATISTICS/Production-and-trade, accessed 7 Sep 2011.
[71] http://data.un.org/, accessed 8 Feb 2011.

information on the likely size of these flows, it is assumed in the ESAM that all S contained within coal ultimately ends up as solid waste released to landfills.

Municipal Wastewater

Similar to solid waste, the calculation of wastewater flows is undertaken at the level of individual countries and then aggregated to provide a global total. The method stipulated in the IPCC Guidelines for calculating wastewater generation originating from household water use is based on per capita emission rates (BOD_5/person/day[72]) that vary between regions (IPCC, 2006). Correction factors are used to account for BOD from different industries co-discharged with domestic wastewater, e.g. restaurants, butchers and supermarkets. Applying these rates, as well as superior data from national inventories where available, the total domestic wastewater generated over the study year is estimated as 61.1 Tg C, assuming an organic C to BOD mass ratio of 0.53 (San Diego-McGlone *et al*., 2000). Ratios of N:BOD and P:BOD are applied to estimate a loading of 22,200 Gg N and 4,240 Gg P. The mass of S in wastewater is derived from the calculated S in sludge (refer to Section 4.3.3), assuming that the proportion of S removed in the sludge, out of total wastewater S, is the same as the proportion of P (van Drecht *et al*., 2009).

Industrial Wastewater

A summary of the C, N, P and S contained within industrial wastewater is provided in Table 5.4. The derivation of industrial wastewater element flows is based on a bottom-up approach involving calculations for nine industry groups: food manufacturing (GTAP industries 19 to 26), pulp and paper manufacturing (31), petroleum refining (32), leather (29), textiles (27), chemicals (33), wood products (30), ferrous metals (35), and other metals (36). For each industry group, the total mass of organic C, TOC, contained within wastewater is derived as,

$$TOC = E \times rWWEC \times CC ,$$

where E denotes the quantity of economic commodities produced by the relevant activity (measured typically in either US$ or tonnes), $rWWEC$ is the rate of wastewater production per unit of produced economic commodity, and CC is the organic C composition of wastewater (gC/g COD[73]). The values of $rWWEC$ for leather, textiles, chemicals, wood products, ferrous

[72] BOD_5 is the amount of dissolved oxygen consumed in five days by biological processes breaking down organic matter.

[73] COD measures the total organic material available for chemical oxidation.

metals, and other metals are expressed as g COD/$US of commodity, and are derived from reported wastewater production values in national GHG inventories, combined with sector output values contained within the GTAP 7.0 database. For the food, pulp and paper, and petroleum manufacturing industries, physical $rWWEC$ rates (i.e. g COD/t) are instead applied (Doorn *et al*., 1997). The relevant data on commodity production, in mass terms, are obtained from the United Nations Industrial Commodity Statistics[74] and FAO ForesSTAT[75] databases.

Table 4.4 Composition of Global Wastewater by Source and Allocation to Global Trade Analysis Project Sectors, 2004

Wastewater Source	C	N	P	S	GTAP Code	Sector Disaggregation Scalar[1]
	Tg	Gg	Gg	Gg		
Municipal wastewater						
Domestic	54.4	19,920	3,800	1,290	100	
Industries and establishments	6.3	2,280	440	150	47-56	$pfGTAP_j$ / $totalpfGTAP_j$
Industrial wastewater						
Food manufacturing	43.9	15,050	220	3,450	19-26	N/A
Textiles	0.6	190	0	60	27	
Leather	0.0	10	0	0	29	
Wood products	0.2	80	0	70	30	
Pulp and paper manufacturing	20.4	6,980	100	6,520	31	
Petroleum refining	0.4	150	0	20	32	
Chemicals	2.8	950	180	0	33	
Ferrous metals	0.1	0	0	0	35	
Other metals	0.0	0	0	5,570	36	

Notes: 1. $pfGTAP_j$ = purchases from food sectors (US$) by sector j from the GTAP 7.0 database; $totalpfGTAP_j$ = total purchases from food sectors (US$) by sectors 19-26 from the GTAP 7.0 database.

San Diego-McGlone *et al*. (2000) provide factors to convert the COD within industrial wastewater to estimates of organic C, N and P content. Estimates of the S content of wastewater are produced for each sector by multiplying the mass of N contained within the sector's wastewater by an assumed ratio of S to N. For industries involved in the processing of animal products (19, 20 and 29), the ratio is based on the stoichiometry of humans (Sterner and Elser, 2002), while for industries 21 and 23–28 the ratios are derived from the calculated element contents of associated crops. In the case of industry 22, a S:N ratio of sewage sludge

[74] http://data.un.org/, accessed 11 Feb 2011.
[75] http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, accessed 11 Feb 2011.

(Werther and Ogada, 1999) is applied, and for industries 30 and 31 the stoichiometry of terrestrial vegetation.[76]

To complete the calculation of industrial wastewater flows, special consideration is given to the generation of inorganic waste S by industrial activities. As already explained, significant quantities of S are consumed in petroleum refining. An average S:COD mass ratio of 0.0092 for petroleum refinery wastewater (Altaş and Büyükgüngör, 2008) enables calculation of inorganic wastewater S for industry 32. Ober (2002) also identifies copper ore processing as a significant producer of waste S originating from the use of sulphuric acid. The US rate of sulphuric acid consumption by copper ore processing is reported as 452,000t S (USGS, 2006). This is scaled to a global estimate of 5.57 Tg S, based on relative output of copper from world mines compared with US mines. [77]

4.3.3 Waste Treatment

This section describes the quantities of wastes that re-enter the economy as reused or recycled materials and the treatment of remaining wastes for final disposal. Although the actual release of waste products into the environment following treatment fits within the residual generation component of the conceptual framework, many of these flows are outlined in this section for convenience.

Crop Residuals

Three principal economic uses of crop residuals are identified: animal feed, biofuels and paper production. Starting with animal feed, these mass flows are calculated as,

$$AF_e = PFC_e \times rPFCR,$$

where AF_e is the mass of element e contained within crop residuals used as feed, $PFCe$ is the mass of element e in pasture and forage crops, and $rPFCR$ is the ratio of crop residuals to pasture and forage crops within global animal feed. The values for $PFCe$ are obtained directly from the crop production calculations described in Section 4.3.1, while $rPFCR$ is derived from Wirsenius (2003). The resulting estimates of crop residuals used for animal feed are 416 Tg C, 5,430 Gg N, 894 Gg P and 2,860 Gg S.

[76] Refer to Section 5.4.1.

[77] http://minerals.usgs.gov/minerals/pubs/country, accessed 12 Feb 2011.

The total mass of crop residual C consumed as household biofuel, 503 Tg, is calculated from estimates of household biofuel emissions, assuming that around 90 percent of crop C is volatised as an emission (Yevich and Logan, 2003). The associated N, P and S flows (6,570 Gg, 1,640 Gg and 3,460 Gg, respectively) are then derived from the C flow, by applying the stoichiometry of crop residuals.[78] According to the work of Yevich and Logan (2003) only a few types of crop residuals are used in significant quantities as industrial fuel. Using Yevich and Logan's (2003) data, and the crop production estimates of Section 4.3.1, the estimates presented in Table 5.5 are generated.

Table 4.5 Crop Residuals Consumed as Industrial Biofuel by Sector, 2004

Residue Type	C	N	P	S	GTAP Sector Code
	Tg	Gg	Gg	Gg	
Coconut residues	1.4	40	0	10	4
Coconut residues, cottonseed hulls, palm kernels	22.3	360	20	100	21
Rice husks and straw	29.6	1,280	60	180	23
Sugar cane bagasse	19.0	190	30	110	24

The FAO's ForesSTAT database records total global production of fibre pulp from materials other than wood and recycled paper as 1.69 Mt. Given the relatively small size of the element flows in question, it is simply assumed that the necessary materials originate entirely from crop residuals, and that approximately half the input materials are wasted during pulp production. The input of crop residuals for paper production is calculated as 30.4 Tg of dry matter, translating to 17.8 Tg C, 232 Gg N, 38.3 Gg P and 122 Gg S based on the stoichiometry of fibrous crops.[79]

The quantities of crop residuals burned within agricultural fields are described in Section 4.3.4. All remaining crop residuals (i.e. the difference between crop residuals production and crop residuals used for animal feed, biofuels and paper production), are calculated to be 891 Tg C, 9,810 Tg N, 1,050 Gg P and 516 Gg S. These are treated as an input from the economy to the litter/detritus stock.

[78] Refer to Section 4.3.1.
[79] Refer to Section 4.3.1.

Livestock excrement

The likely fate of C, N, P, and S contained within excrement produced by livestock varies across the world depending on farming practices. Grazing animals are assumed to deposit their wastes directly onto land. These flows (Table 5.6) are calculated by multiplying the estimates of manure production by livestock type, by the proportion of the livestock population not reared in confinement (Smil, 1999). Of the excrement N discharged directly to land, 22 percent is treated as a flow to the atmospheric NH_3 stock, due to the almost immediate volatisation of this gas (Laubach *et al*. 2013). The remaining elements contained within these flows are treated as a discharge from the economy to the litter/detritus stock.

The N content of manures from confined animals is greatly reduced during collection, storage and handling of the wastes. The proportions of collected manure N volatised as NH_3 are taken from Smil (1999) and range from 28 to 36 percent depending on livestock type. Total emissions of NH_3 are calculated as 14,760 Gg. N_2O is also produced during manure storage and treatment via the combined processes of nitrification and denitrification. The literature generally agrees that N_2O production requires the presence of either nitrites or nitrates in an anaerobic environment. Additionally, conditions preventing reduction of N_2O to N_2, such as a low pH or limited moisture, must be present (IPCC, 2006). The IPCC Tier 1 method for estimating N_2O emissions entails allocating the total amount of N excretion from all livestock species to different types of manure management systems, and then multiplying by an emission factor for each type of system. This approach produces a global N_2O emission rate of 447 Gg.

Total household consumption of manure as a fuel is estimated as 68.6 Tg C, 5,780 Gg N and 516 Gg P; based on the biofuel emissions (refer to Section 4.3.4) while accounting for a proportion that escapes combustion. The remaining mass contained within excrement produced by confined animals, calculated as 252 Tg C, 21,200 Gg N and 1,890 Gg P, must be released from agricultural systems back into the environment. While the majority of these wastes will be employed as a form of fertiliser (Smil, 1999), a proportion is also released as waste. In either case, the flows are treated as inputs to the litter/detritus stock. Upon application to soils, a further 15 percent of the N in excrement is volatised as NH_3 (Smil, 1999).

Table 4.6 Livestock Excrement Production and Manure Management Element0 Flows, 2004

Livestock type	Total production			Excrement produced in confinement			NH_3 & N_2O losses from manure management[1]	GTAP Sector
	C	N	P	C	N	P	N	
	Tg	Gg	Gg	Tg	Gg	Gg	Gg	
Asses	7.2	1,500	40	3.6	750	20	220	9
Buffaloes	21.0	6,360	450	7.3	2,220	160	630	9
Camels	4.1	91	10	2.0	50	10	10	10
Cattle	308.4	66,430	1,280	113.8	24,510	470	9,140	9,11[2]
Chickens	87.3	5,270	1,150	87.3	5,270	1,150	1,900	10
Ducks	5.6	340	70	5.1	310	70	110	10
Geese & guinea fowl	1.6	100	20	1.5	90	20	30	10
Goats	43.5	3,630	740	4.4	360	70	110	9
Horses	10.0	2,080	60	5.0	1,040	30	300	9
Mules	2.1	440	10	1.1	220	10	60	9
Other camelids	1.2	30	0	0.6	10	0	0	10
Other rodents	1.1	70	10	1.1	70	10	20	10
Pigs	80.5	5,900	170	80.5	5,900	170	2,200	10
Sheep	40.5	4,780	350	4.0	480	30	140	9,12[3]
Turkeys	2.8	830	180	2.8	830	180	310	10
Animals live NES	0.6	110	10	0.4	70	10	20	10
Total	617.4	97,950	4,570	320.3	42,170	2,410	15,210	

Notes: 1. From confined livestock only. 2. 78% Sector 9, 22% Sector 11. 3. 40% Sector 9, 60% Sector 12.

Solid Wastes

Four broad types of treatment practices for solid wastes are covered: recycling/reuse, incineration, composting and release to landfills. As with other waste-related flows, there is very little information at a global level to determine the quantities of wastes undergoing these different treatments. The proportions by which total waste materials are distributed among waste treatment options are summarised in Table 5.7.

Table 4.7 Distribution of Municipal and Industrial Solid Waste Materials among Waste Treatment Options[1,2]

Waste Type	Recycling/ Re-use	Incineration[7]	Composting[7]	Landfill[7]
Paper/ card board	40%[4]	10%	4%	45%
Textiles	33%[5]	14%	1%	52%
Vegetable/ animal[3]	0%	8%	9%	82%
Rubber/ leather	22%[5]	12%	0%	66%
Plastics	32%[5]	11%	0%	57%
Petroleum products/ solvents	18%[5]	6%	0%	76%
Wood (construction and demolition)	21%[6]	31%	0%	48%
Wood (municipal)	0%	11%	6%	83%

Notes: 1. All values are expressed as a share of waste mass. 2. All waste recycling/ re-use treatment flows are allocated to GTAP Sector 42; Incineration, composting and landfill treatment flows for municipal solid waste are allocated to GTAP Sector 56; Incineration, composting, and landfill treatment of industrial solid wastes are assigned to GTAP industrial sectors on a pro-rata basis according to the relative quantities of solid wastes produced within each sector. 3. Excludes biogenic wastes from rural populations in developing countries. 4. Based on pulp and paper production data from the FAO. 5. Derived by comparing the rate of recycling/reuse in the EU for this waste type with the rate of paper recycling. 6. Informed by data reported by Symonds Group Ltd (1999). 7. Derived out of treatment rates specified in the IPCC Guidelines for National GHG Inventories (IPCC, 2006).

The C contained within incinerated and composted wastes, is treated as direct atmospheric emissions of CO_2 and CH_4. The EDGAR database records global CH_4 emissions from waste incineration and other waste handling (assumed to include composting) as together less than 1 Tg C. Even when adjusting for missing country data, the estimated CH_4 emissions are less than 1 Tg C. The remaining C within composted and incinerated wastes, respectively calculated as 59.3 Tg and 18.6 Tg, is assigned as a flow to atmospheric CO_2. All N, P, and S within composted wastes are assigned simply as a flow to the respective element soil inorganic stocks. As with C, it is assumed that N, P, and S are all released into the environment during the year in which the wastes are generated, although in reality composting rates may be slower.

Accounting for residual generation from incinerated wastes is more complex due to the production of N and S gas emissions. Emissions of N_2, NO_x, N_2O and NH_3 are estimated from emission factors (e.g. t NH_3–N per t of waste N) which are, in turn, derived from national GHG inventories for residential biofuels and wood processing wastes (Section 4.3.4). The resulting emissions are 231 Gg N_2–N, 74 Gg NO_x–N, 3 Gg N_2O–N and 152 Gg NH_3–N. Approximately half the N contained within incinerated wastes remains following subtraction of gaseous emissions, and is treated as a residual flow to the litter/detritus stock. Similarly, the P content of incinerated wastes is assigned as a flow to the litter/detritus stock, while for S, the element content is assigned entirely to a gaseous emission of SO_2.

The release of solid wastes into disposal sites is considered the point at which wastes leave the economy. Nevertheless, the procedure for calculating gaseous emissions from landfills is specified in this chapter. The IPCC (2006) methodology for estimating CH_4 emissions from solid waste disposal sites is based on a first order decay function, which assumes that the rate of DOC loss from wastes is highest in the first few years of deposition, and then gradually declines as the C is consumed. This method requires historical waste disposal data in order to estimate present day emissions. In this instance, landfilled solid waste is back caste 55 years from the study year based on the rate of change in real GDP.[80] The estimated DOC decomposed at solid waste disposal sites based on the IPCC methodology is 56.8 Tg. Of the DOC decomposed, the default proportion released immediately as CH_4 is 50 percent. A proportion of the CH_4 produced may, however, oxidise relatively quickly to CO_2. The default IPCC value for CH_4 oxidation is zero, although according to the guidelines values of up to 10 percent may apply in well-managed solid waste disposal sites. A value of 3 percent is applied in this thesis, producing a global emission for CH_4, 27.6 Tg C, and CO_2, 29.3 Tg C.

Wastewater

Wastewater treatment and discharge methods vary significantly between countries, and between rural and urban locations. Applying parameters specified in the IPCC guidelines for national GHG inventories (IPCC, 2006), it is estimated that around 54 percent of total domestic wastewater (measured in C terms) passes through sewers, 22 percent is discharged to latrines, 9 percent to septic tanks and the remainder is assumed untreated. Wastewater channelled by sewers to centralised treatment plants may undergo primary, secondary and tertiary treatment, with all stages resulting in the production of sewage sludge. Applying region-

[80] http://unstats.un.org/unsd/snaama/dnllist.asp.

specific rates for N and P removal in wastewater treatment (van Drecht *et al*., 2009), and accounting for additional N removed through N_2O and NH_3 emissions, it is estimated that around 1,140 Gg N and 862 Gg P is removed from domestic wastewater in sludge. The C and S contained within sludge, respectively 7.81 Tg and 285 Gg, is also derived from the calculated N content, based on reported ratios of N:C and N:S (Werther and Ogada, 1999). These sewage sludge residuals are allocated to the landfill solid waste stocks by element.

The remaining C, N, P and S contained within domestic wastewater is also discharged to the environment. Applying parameters specified by San Diego-McGlone *et al*. (2000) regarding the apportionment of untreated effluent among organic and inorganic species, 60 percent of the remaining N, and 50 percent of the remaining P, are assigned as flows to the terrestrial soil organic stocks, and the balance to the soil inorganic stocks by element. In the case of S, the same shares as P are applied. The IPCC guidelines specify a default maximum C emission capacity for domestic wastewater of 0.6 kg per kg of wastewater BOD. Applying this value to the total estimated domestic wastewater production, and then subtracting estimated CH_4 emissions from wastewater handling, gives a CO_2 emission flow of 32.8 Tg. The remaining 4.8 Tg of wastewater C is assigned as a discharge to the soil organic C stock.

Finally, in order to allocate industrial wastewater C, N, P, and S to receiving environmental stocks, it is assumed that treatment processes for industrial wastewater in each country are approximately equivalent to that of domestic wastewater (Table 5.8). Note, however, that the flow of inorganic wastewater S includes waste S produced during copper ore processing and petroleum refining.

Table 4.8 Inputs to Environmental Stocks Resulting from Wastewater Treatment and Discharge by Global Trade Analysis Project Sector, 2004

GTAP Code	GTAP Name	Atmosphere stocks				Landfills				Soil organic				Soil inorganic		
		CO_2	CH_4	N_2O	NH_3	C	N	P	S	C	N	P	S	N	P	S
		Tg C	Tg C	Gg N	Gg N	Tg C	Gg	Gg	Gg	Tg	Gg	Gg	Gg	Gg	Gg	Gg
Industrial Wastewater																
19	Cattle, sheep meat	0.2	0.2	0	40	0.5	70	0	0	0.2	160	0	10	110	0	10
20	Other meat	0.5	0.4	10	100	1.4	210	10	0	0.4	360	0	30	240	0	30
21	Vegetable oils	0.0	0.0	0	2	0.0	0	0	0	0.0	0	0	0	10	0	0
22	Dairy products	0.1	0.1	0	40	0.5	80	0	0	0.1	110	0	30	70	0	30
23	Processed rice	2.3	2.4	30	300	4.1	590	20	0	1.7	1,630	20	260	1,080	20	260
24	Sugar cane	1.1	2.0	20	200	2.7	390	10	0	1.8	1,200	10	750	800	10	750
25	Other food	2.7	2.7	70	720	9.8	1,430	40	0	1.8	2,180	20	500	1,450	20	500
26	Beverages, tobacco	0.6	0.7	10	150	2.1	300	10	0	0.5	530	10	140	350	10	140
27	Textiles	0.2	0.1	0	20	0.3	40	0	0	0.0	80	0	30	50	0	30
28	Wearing apparel	0.0	0.0	0	0	0.0	0	0	0	0.0	0	0	0	0	0	0
29	Leather products	0.0	0.0	0	0	0.0	0	0	0	0.0	0	0	0	0	0	0
30	Wood products	0.0	0.0	0	10	0.1	20	0	0	0.0	30	0	40	20	0	40
31	Paper products	3.6	3.5	80	890	12.3	1,780	50	0	1.0	2,530	30	3,260	1,690	30	3,260
32	Petroleum	0.1	0.1	0	20	0.2	30	0	0	0.0	60	0	0	40	0	20
33	Chemicals, rubber	0.7	0.4	10	120	1.6	240	80	10	0.0	350	50	0	230	50	0
34	Mineral products	0.0	0.0	0	0	0.0	0	0	0	0.0	0	0	0	0	0	0
35	Ferrous metals	0.0	0.0	0	0	0.0	0	0	0	0.0	0	0	0	0	0	0
36	Other metals	0.0	0.0	0	0	0.0	0	0	0	0.0	0	0	0	0	0	5,570
Domestic Wastewater																
56	Other services (government)	17.9	4.9	230	2,460	7.8	1,140	860	280	0.5	4,550	660	220	4,550	660	220
100	Households	14.9	10.3	0	0	0.0	0	0	0	4.3	6,480	1,030	350	4,320	1,030	350
	Total	44.9	28.0	470	5,060	43.5	6,340	1,070	300	12.4	20,240	1,830	5,620	13,500	1,830	11,200

4.3.4 Residual Generation

Atmospheric emissions

Tables 4.9–4.11 provide a summary of the different types of atmospheric emission flows included in the ESAM, and the relevant literature/data sources used in estimating each flow. Note that the adopted fossil fuel SO_2 emission flow (excluding international shipping) of 45,800 Gg S is comprised of ten separate emission sub-categories within the EDGAR database, with the most important being public electricity and heat production (62 percent of the total emission) and manufacturing industries and construction (23 percent). The flow for public electricity and heat production is allocated entirely to industry 43. The manufacturing and construction flow is split on a pro-rata basis among industries 18–42 and 46 using independently derived estimates of SO_2 emissions from combustion in these sectors. These estimates are derived by first calculating the C content of coal, crude oil and petroleum products combusted within each industry, based on data recorded in the GTAP 7.0 database. The quantities of C within fuels are then converted to quantities of S based on average C:S ratios, and finally multiplied by fuel-specific scalars describing the proportion of fuel S oxidised during combustion (IPCC,2006).

Table 4.9 Derivation of Adopted Atmospheric Carbon Emission Rates and Disaggregation to Global Trade Analysis Project Sectors

	Emission species	Emission activity	Literature/Data Sources	Reported annual emission	Emission Adopted in this Study	Comments	GTAP Code	Sector Disaggregation Scalar
(1)	CO_2	Fossil fuels (excl. fugitive)	Prentice *et al*. (2001)[1] Denman *et al*. (2007)[1] Boden (2012)[1]	6,400 Tg C 7,200 Tg C 7,812 Tg C	6,784.4 Tg C	Derived from Boden (2012), less adopted emissions of methane, CO and VOC from fossil fuels, cement and lime production emissions and fugitive emissions.	1-56, 100	$cdGTAP_j/totalcdGTAP$
(2)	CO_2	Cement and lime production	EDGAR	298.7 Tg C	298.7 Tg C		34	
(3)	CO_2	Mineral production (excl. cement & lime)	EDGAR	13.5 Tg C	13.5 Tg C		34	
(4)	CO_2	Chemical production	EDGAR	106 Tg C	106 Tg C		33	
(5)	CO_2	Metal production	EDGAR	49.3 Tg C	49.3 Tg C		35, 36	$GTAPoutput_j/totalGTAPoutput$
(6)	CO_2	Domestic animal respiration			1,606.3 Tg C	Derived from bottom-up calculation applying livestock emission factors from Prairie & Duarte (2007).	9-12	N/A
(7)	CO_2	Field burning of agricultural residuals	Andreae & Merlet (2001)	223 Tg C	240.6 Tg C	The Andreae & Merlet (2001) estimate is for the late 1990s.	1-8	$agresiduals^e_j/totalagresiduals^e$
(8)	CO_2	Industrial biofuels - crop residuals			57.7 Tg C	Derived from information provided by Yevich & Logan (2003) and the share of emission species in the adopted emissions for domestic biofuels.	4, 21, 23, 24	$indcropbio^e_j/totalindcropbio^e$
(9)	CO_2	Industrial biofuels - wood residuals			140.5 Tg C	Derived from bottom-up calculation.	30, 31	N/A
(10)	CO_2	Domestic biofuels	Ito & Penner (2004)	1,060 Tg C	1,059 Tg C	The Ito & Penner (2004) estimate includes charcoal burning and is for 2000. Once emissions from charcoal are subtracted the estimate is scaled to 2004 based on growth in total biomass extraction (Krausmann *et al*. 2009).	100	
(11)	CO_2	Charcoal making and burning	Andreae & Merlet (2001)	46.1 Tg C	46.1 Tg C		100	
(12)	CO_2	Human respiration			601.4 Tg C	Derived from human emission rate reported by Prairie & Duarte (2007).	100	
(13)	CH_4	Fossil fuels (excl. fugitive)	EDGAR	9.7 Tg C	9.7 Tg C		1-56, 100	$cdGTAP_j/totalcdGTAP$
(14)	CH_4	Chemical production	EDGAR	0.1 Tg C	0.1 Tg C		33	
(15)	CH_4	Metal production	EDGAR	0.1 Tg C	0.1 Tg C		35, 36	$GTAPoutput_j/totalGTAPoutput$
(16)	CH_4	Ruminants	Prather *et al*. (1995) Hein *et al*. (1997) Weubbles & Hayhoe (2002) Scheehle *et al*. (2002) Wang *et al*. (2004) Mikaloff Fletcher *et al*. (2004) Olivier *et al*. (2005)	63.6 Tg C 68.9 Tg C 60.6 Tg C 56.9 Tg C 62.1 Tg C 68.1 Tg C 59.9 Tg C	60.9 Tg C	The adopted value is an mean of the estimates of Weubbles & Hayhoe (2002), Wang *et al*. (2004) and Olivier *et al*. (2005).	9-12	$entericf_j/totalentericf$

Table 4.9 Derivation of Adopted Atmospheric Carbon Emission Rates and Disaggregation to Global Trade Analysis Project Sectors (Cont.)

	Emission species	Emission activity	Literature/Data Sources	Reported annual emission	Emission Adopted in this Study	Comments	GTAP Code	Sector Disaggregation Scalar
(17)	CH_4	Field burning of agricultural residuals	Andreae & Merlet (2001)	1.1 Tg C	1.6 Tg C	See comment for (7). The estimate is then adjusted to ensure that total CH_4 emissions from all biomass burning match estimates by Weubbles & Hayhoe (2002) and Wang *et al*. (2004).	1-8	$agresiduals^e_j / totalagresiduals^e$
(18)	CH_4	Industrial biofuels - crop residuals			1 Tg C	See comment for (8).	4, 21, 23, 24	$indcropbio^e_j / totalindcropbio^e$
(19)	CH_4	Industrial biofuels - wood residuals			2.5 Tg C	See comment for (9).	30, 31	N/A
(20)	CH_4	Domestic biofuels	Ito & Penner (2004)	12.3 Tg C	19 Tg C	See comments for (10) and (17).	100	
(21)	CH_4	Charcoal making and burning	Andreae & Merlet (2001)	1.5 Tg C	2.2 Tg C	See comment for (17).	100	
(22)	CH_4	Humans (direct)	Crutzen *et al*. (1986) Lerner *et al*. (1988)	0.7 Tg C 0.7 Tg C	0.7 Tg C		100	
(23)	CO	Fossil fuels (excl. fugitive)	Prather & Ehhalt (2001)	278.7 Tg C	340.2 Tg C	Scaled to reflect greater total C emission estimate of Boden (2012).	1-56, 100	$cdGTAP_j / totalcdGTAP$
(24)	CO	Field burning of agricultural residuals	Andreae & Merlet (2001)	21.4 Tg C	23.1 Tg C	See comment for (7).	1-8	$agresiduals^e_j / totalagresiduals^e$
(25)	CO	Industrial biofuels - crop residuals			5.4 Tg C	See comment for (8).	4, 21, 23, 24	$indcropbio^e_j / totalindcropbio^e$
(26)	CO	Industrial biofuels - wood residuals			13.1 Tg C	See comment for (9).	30, 31	N/A
(27)	CO	Domestic biofuels	Ito & Penner (2004)	99.5 Tg C	98.6 Tg C	See comment for (10).	100	
(28)	CO	Charcoal making and burning	Andreae & Merlet (2001)	8 Tg C	8 Tg C		100	
(29)	VOCs	Fossil fuels (excl. fugitive)	Prather & Ehhalt (2001)	161 Tg C	196.5 Tg C	See comment for (23).		
(29)	VOCs	Field burning of agricultural residuals	Andreae & Merlet (2001)	3.1 Tg C	3.3 Tg C	See comment for (7).	1-8	$agresiduals^e_j / totalagresiduals^e$
(30)	VOCs	Industrial biofuels - crop residuals			0.9 Tg C	See comment for (8).	4, 21, 23, 24	$indcropbio^e_j / totalindcropbio^e$
(31)	VOCs	Industrial biofuels - wood residuals			2.3 Tg C	See comment for (9).	30, 31	N/A
(32)	VOCs	Domestic biofuels	Ito & Penner (2004)	17 Tg C	17.2 Tg C	See comment for (10).	100	
(33)	VOCs	Charcoal making and burning	Andreae & Merlet (2001)	0.4 Tg C	0.4 Tg C		100	

Notes: 1. Includes other trace carbon gases, fugitive emissions and cement and lime production emissions. 2. Refer to the International Energy Agency's World Energy Balance (http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=29, accessed 16 Jan 2013).

Table 4.10 Derivation of Adopted Atmospheric Nitrogen Emission Rates and Disaggregation to Global Trade Analysis Project Sectors

Emission species	Emission activity	Literature/Data Sources	Reported annual emission	Emission Adopted in this Study	Comments	GTAP Code	Sector Disaggregation Scalar
(1) N_2	Fossil fuels			19,640 Gg N	Assumes 30% of fossil fuel N is released as N_2 (Schlesinger, 1997) and that 10 percent of oil is used as a feedstock for chemcial manufacturing.	1-56, 100	$cdGTAP_j/totalcdGTAP$
(2) N_2	Field burning of agricultural residuals	Andreae & Merlet (2001)	850 Gg N	920 Gg N	Andreae & Merlet's (2001) estimate is for the late 1990s.	1-8	$agresiduals^e{}_j/totalagresiduals^e$
(3) N_2	Industrial biofuels - crop residuals			420 Gg N	Derived from information provided by Yevich & Logan (2003) and the share of emission species in the adopted emissions for domestic biofuels.	4, 21, 23, 24	$indcropbio^e{}_j/totalindcropbio^e$
(4) N_2	Industrial biofuels - wood residuals			520 Gg N	The adopted CO_2 emissions are multiplied by an estimated ratio of the N species to CO_2 derived from Andrea & Merlet (2002).	30, 31	N/A
(5) N_2	Domestic biofuels	Andreae & Merlet (2001)	4,200 Gg N	3,890 Gg N	See comment for (4).	100	
(6) N_2	Charcoal making and burning	Andreae & Merlet (2001)	60 Gg N	60 Gg N		100	
(7) NO_x	Fossil fuels (excl. from N_2 fixation)	Galloway & Cowling (2002)	21,000 Gg N	16,700 Gg N	Galloway & Cowling's (2002) estimate includes emissions from N_2 fixation and is for 1990.	1-56, 100	$cdGTAP_j/totalcdGTAP$
(8) NO_x	Field burning of agricultural residuals	Andreae & Merlet (2001)	610 Gg N	650 Gg N	See comment for (2).	1-8	$agresiduals^e{}_j/totalagresiduals^e$
(9) NO_x	Industrial biofuels - crop residuals			140 Gg N	See comment for (3).	4, 21, 23, 24	$indcropbio^e{}_j/totalindcropbio^e$
(10) NO_x	Industrial biofuels - wood residuals			170 Gg N	See comment for (4).	30, 31	N/A
(11) NO_x	Domestic biofuels	Andreae & Merlet (2001)	1,350 Gg N	1,250 Gg N	See comment for (4).	100	
(12) NO_x	Charcoal making and burning	Andreae & Merlet (2001)	70 Gg N	70 Gg N		100	
(13) N_2O	Total fossil fuels and industrial processes	Denman *et al*. (2007)	200 - 1,800 Gg N	920 Gg N	Derived by taking the mid point of the range reported by Denman *et al*. (2007), which is for the 1990s, and scaling upwards based on growth in world GDP.	N/A	
(14) N_2O	Fossil fuels			560 Gg N	The adopted emission for (13) is shared among fossil fuels and other industrial processes based on relative shares in EDGAR.	1-56, 100	$cdGTAP_j/totalcdGTAP$
(15) N_2O	Production of chemicals			310 Gg N	See comment for (14).	33	
(16) N_2O	Solvent and other product use			40 Gg N	See comment for (14).	56	

Table 4.10 Derivation of Adopted Atmospheric Nitrogen Emission Rates and Disaggregation to Global Trade Analysis Project Sectors (Cont.)

Emission species	Emission activity	Literature/Data Sources	Reported annual emission	Emission Adopted in this Study	Comments	GTAP Code	Sector Disaggregation Scalar
(17) N_2O	Manure management			450 Gg N	Derived from a bottom-up approach applying emission estimates for different livestock types.	9-12	N/A
(18) N_2O	Field burning of agricultural residuals	Andreae & Merlet (2001)	10 Gg N	10 Gg N	See comment for (2).	1-8	$agresiduals^e_j/totalagresiduals^e$
(19) N_2O	Industrial biofuels - crop residuals			<10 Gg N	See comment for (3).	4, 21, 23, 24	$indcropbio^e_j/totalindcropbio^e$
(20) N_2O	Industrial biofuels - wood residuals			<10 Gg N	See comment for (4).	30, 31	N/A
(21) N_2O	Domestic biofuels	Andreae & Merlet (2001)	50 Gg N	50 Gg N	See comment for (4).	100	
(22) N_2O	Charcoal making and burning	Andreae & Merlet (2001)	<10 Gg N	<10 Gg N		100	
(23) NH_3	Total fossil fuels and industrial processes	Denman *et al*. (2007)	2,500 Gg N	3,410 Gg N	The value reported by Denman *et al*. (2007), which is for the 1990s, is scaled upwards based on growth in World GDP.	N/A	
(24) NH_3	Fossil fuels			630 Gg N	The adopted emission for (23) is shared among fossil fuels and other industrial processes based on relative shares in EDGAR.	1-56, 100	$cdGTAP_j/totalcdGTAP$
(25) NH_3	Production of minerals			30 Gg N	See comment for (24).	34	
(26) NH_3	Production of chemicals			2,750 Gg N	See comment for (24).	33	
(27) NH_3	Synthetic fertilisers			12,940 Gg N	Derived from data in Bouwman *et al*. (2002) and fertiliser consumption statistics.	1-12	N/A
(28) NH_3	Manure discharged directly to fields			12,270 Gg N	Assumes 22% of N discharged directly to fields is volatised (Lauback *et al*., 2013).	9-12	$nclsmanure^n_j/totalnclsmanure^n$
(29) NH_3	Manure management			14,760 Gg N	See comment for (17).	9-12	N/A
(30) NH_3	Collected manure discharged to fields			3,180 Gg N	Assumes 15% of N in collected excrement discharged on fields is volatised (Smil, 1999).	1-12	N/A
(31) NH_3	Field burning of agricultural residues	Andreae & Merlet (2001)	1,070 Gg N	1,150 Gg N	See comment for CO_2 emissions from field burning of agricultural residues.	1-8	$agresiduals^e_j/totalagresiduals^e$
(32) NH_3	Industrial biofuels - crop residues			250 Gg N	See comment for (3).	4, 21, 23, 24	$indcropbio^e_j/totalindcropbio^e$
(33) NH_3	Industrial biofuels - wood residues			350 Gg N	See comment for (4).	30, 31	N/A
(34) NH_3	Domestic biofuels	Andreae & Merlet (2001)	2,880 Gg N	2,670 Gg N	See comment for (4).	100	
(35) NH_3	Charcoal making and burning	Andreae & Merlet (2001)	50 Gg N	50 Gg N		100	
(36) NH_3	Human breath, sweat	Denman *et al*. (2007)	2,600 Gg N	400 Gg N	The Denman *et al*. (2007) estimate is for all human excreta emissions.	100	

Table 4.11 Derivation of Adopted Atmospheric Sulphur Emission Rates and Disaggregation to Global Trade Analysis Project Sectors

	Emission species	Emission activity	Literature/Data Sources	Reported annual emission	Emission Adopted in this Study	Comments	GTAP Code	Sector Disaggregation Scalar
(1)	SO_2	Fossil fuels (excl. international shipping)	EDGAR	45,770 Gg S	45,770 Gg S		1-43, 46-56,100	N/A
(2)	SO_2	International shipping	Smith *et al*. (2010)	4,900 Gg S for 2000 6,050 Gg S for 2005	5,800 Gg S		49	
(3)	SO_2	Production of chemicals	EDGAR	2,050 Gg S	2,050 Gg S		33	
(4)	SO_2	Production of metals	EDGAR	5,260 Gg S	5,260 Gg S		36	
(5)	SO_2	Production of pulp, paper, food, drink	EDGAR	170 Gg S	170 Gg S		19-26, 31	$(wwater^s_j + solidw^s_j)/(totalwwater^s + totalsolidw^s)$
(6)	SO_2	Field burning of agricultural residuals	Andreae & Merlet (2001)	110 Gg S	120 Gg S	The Andreae & Merlet estimate is for the late 1990s.	1-8	$agresiduals^e_i/totalagresiduals^e$
(7)	SO_2	Industrial biofuels - crop residuals			30 Gg S	The estimated CO_2 emissions are multiplied by a ratio for the S species to CO_2 derived from Andreae & Merlet (2001).	4, 21, 23, 24	$indcropbio^e_j/totalindcropbio^e$
(8)	SO_2	Industrial biofuels - wood residuals			50 Gg S	See comment for (7).	30, 31	N/A
(9)	SO_2	Domestic biofuels	Andreae & Merlet (2001)	370 Gg S	340 Gg S	See comment for (7).	100	
(10)	SO_2	Charcoal making and burning	Andreae & Merlet (2001)	10 Gg S	10 Gg S		100	
(11)	CS_2	Total anthropogenic (excl. rice agr.)	Watts (2000)	290 Gg S	330 Gg S	Watt's estimate is for 2000. It is scaled to 2004 based on GDP growth.	1-56, 100	$nonbiosd_j/totalnonbiosd$
(12)	OCS	Vehicle emissions	Watts (2000)	<10 Gg S	<10 Gg S		48, 100	
(13)	OCS	Coal combustion	Watts (2000)		20 Gg S	Watts' estimate is for 2000. It is scaled to 2004 based on growth in coal production (Taylor *et al*., 2006).	1-56, 100	$cdGTAPcp_j/totalcdGTAPcp$
(14)	OCS	Aluminium production	Watts (2000)	40 Gg S	50 Gg S	Watts estimate is for 2000. It is scaled to 2004 based on growth in aluminium production (Taylor *et al*., 2006).	36	
(15)	OCS	Industrial S recovery	Watts (2000)	<10 Gg S	<10 Gg S	Sector disaggregation based on relative production of S in the US as a by-product of metallurgy, natural gas and petroleum production (USGS, 2006).	17, 32, 36	
(16)	OCS	Field burning of agricultural residuals			<10 Gg S	Derived from Watts (2000), Andreae & Merlet (2001) and relative CO_2 emissions for different types of biomass burning activities.	1-8	$agresiduals^e_j/totalagresiduals^e$
(17)	OCS	Industrial biofuels - crop residuals			<10 Gg S	See comment for (16).	4, 21, 23, 24	$indcropbio^e_j/totalindcropbio^e$
(18)	OCS	Industrial biofuels - wood residuals			<10 Gg S	See comment for (16).	30, 31	N/A
(19)	OCS	Domestic biofuels			20 Gg S	See comment for (16).	100	
(20)	OCS	Charcoal making and burning			<10 Gg S	See comment for (16).	100	
(21)	H_2S	Total anthropogenic (excl. rice agr.)	Watts (2000)	3,100 Gg S	3,550 Gg S	See comment for (11).	1-56, 100	$nonbiosd_j/totalnonbiosd$
(22)	DMS	Total anthropogenic (excl. rice agr., crop emissions)	Watts (2000)	70 Gg S	80 Gg S	See comment for (11).	1-56, 100	$nonbiosd_j/totalnonbiosd$

The emission estimates noted in Tables 4.9–4.11 for industrial biofuels-wood residuals for each element are a sum of the estimated emissions from combustion of residuals generated during wood product and paper product manufacturing. For the wood product manufacturing industry, it is assumed that all wood residuals generated during production are combusted. A global mass balance table for wood product manufacturing sector is constructed that, based on the quantities of raw material inputs, estimates the quantities of wood residuals generated. As part of these calculations it is assumed: (1) around 12 percent of raw timber is bark (Krausmann *et al*., 2008); (2) approximately 60 percent of the mass of harvested timber, excluding fuel wood, is used in manufacturing sawn wood, sleepers and wood based panels, with a residual generation rate of around one-third;[81] (3) and a further 9 percent of harvested timber is used in manufacturing other wood products,[82] with a residual generation rate of around 45 percent (Fujimori and Matsuoka, 2007). Altogether, wood residuals of nearly 150 Tg C are estimated for the industry.

Constructing a mass balance table for the global paper product manufacturing industry is similarly complex. Based on the reported production of pulpwood in ForesSTAT,[83] it is estimated that around 15 percent of total forest timber removals are used for paper manufacturing. Adding to this inputs of recovered paper and crop residuals[84], gives a total input of some 232 Tg C to the industry. Of the C inputs to paper production, 62 percent is accounted for in the mass of finished products,[85] and a further 9 percent is already included in the wastewater treatment accounts (Table 4.8). The remaining C is split among combusted black liquor (51.6 Tg), other combusted residuals (10.4 Tg) and solid wastes (5.5 Tg) (Côté *et al*., 2002; USEPA, 2010).

Residuals disposed to land

Four principal mass flow categories are covered: crop residuals, synthetic fertilisers, agricultural chemicals, and livestock excrement (Table 4.12). The first and last categories are

[81] FAO ForesSTAT database, http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, accessed 11 Feb 2011.
[82] FAO ForesSTAT database, http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, accessed 11 Feb 2011.
[83] FAO ForesSTAT database, http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, accessed 11 Feb 2011.
[84] Refer to Section 4.3.3.
[85] The FAO ForesSTAT database records a total paper and paperboard production as 354 Mt for 2004 (http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, accessed 11 February 2011). This is adjusted to 360 Mt based on estimates of production in countries for which data is absent. The assumed DOC content of paper is 40 percent.

calculated in Section 4.3.3. Turning therefore to synthetic fertilisers, Tenkorang and Lowenbert-DeBoer (2008) estimate the total content of fertilisers as 90,700 Gg N and 15,970 Gg P. Unfortunately, the quantity of S contained within global fertilisers is less well understood. Ober (2002), however, estimates that around 210 Gg S ended up in US N fertilisers during 2000. Given that global N fertiliser production in 2004 was about 9.5 times the US production in 2000,[86] the total fertiliser S flow is set as 1,990 Gg. Fertiliser N and P is shared among three different farming types (fertilised grasslands, crops and wetland rice), based on data recorded in Bouwman and Boumans (2002), and assumed N:P ratios for fertiliser.[87] The S and P contained within synthetic fertilisers are treated as direct flows from the economy to the soil inorganic stocks by element. In the case of N, however, the situation is more complex due to the volitisation of NH_3. Total NH_3 losses are calculated as 12,900 Gg N (Bouwman and Boumans, 2002), leaving a flow of 77,800 Gg N to the soil inorganic N stock.

In terms of agricultural chemicals applied to land, the USGS (2006) reports that around 2,030 Gg S were used in the production of pesticides and other agricultural chemicals in the US. It is assumed that local consumption of these chemicals equates to around 94 percent of production, and that the US market is around 35 percent of the world market (KRS Network, 2006). If most of the S used for production ends up in final products, the global flow from the economy to soil inorganic S stock can be estimated as 5,430 Gg.

[86] http://faostat.fao.org/site/575/default.aspx#ancor, accessed 18 Aug 2011.
[87] http://www.fao.org/ag/agl/fertistat/, accessed 18 Aug 2011.

Table 4.12 Residuals Discharged to Land (Excluding Solid Waste and Wastewater Discharge), 2004

Residual type	C	N	P	S	GTAP Code	Sector Disaggregation Scalar[2]
	Tg	Gg	Gg	Gg		
Crop residuals	750	9,810	1,050	5,160	1-8	$agresiduals^{e}{}_{j}/totalagresiduals^{e}$
Synthetic fertilisers[1]						
Upland crops		61,950	13,200	1,650	2-8	N and P: $fertcrop^{e}{}_{j}/totalfertcrop^{e}$ S: $cropfert^{p}{}_{j}/totalcropfert^{p}$
Wetland rice		11,060	2,140	270	1	
Fertilised grasslands		4,740	640	80	9-12	$nclsmanure^{e}{}_{j}/totalnclsmanure^{e}{}_{j}$
Agricultural chemicals				5,430	1-12	$pcGTAP_{j}/totalpcGTAP$
Confined livestock excrement[1,3]						
Upland crops	132	9,480	1,000	8,020	2-8	$GTAPoutput_{j}/totalGTAPoutput$
Wetland rice	25	1,780	190	1,510	1	
Fertilised grasslands	94	6,750	710	5,710	9-12	$GTAPoutput_{j}/totalGTAPoutput$
Non-confined livestock excrement[1]	297	43,500	2,160	17,370	9-12	$nclsmanure^{e}{}_{j}/totalnclsmanure^{e}{}_{j}$

Notes: 1 Excludes NH_3 volatised on release. 2 $agresiduals^{e}_{j}$ = element e in above ground residuals produced from sector j crops; $totalagresiduals^{e}$ = total element e in aboveground residuals produced by sector 1–8 crops; $fertcrop^{e}_{j}$ = element e in synthetic fertilisers applied to sector j crops (FAO, 2006); $totalfertcrop^{e}_{j}$ = total element e in synthetic fertilisers applied to all sector 2–8 crops (FAO, 2006); $cropfert^{p}_{j}$ = estimated synthetic fertiliser p applied to sector j crops; $totalcropfert^{p}$ = total estimated synthetic fertiliser p applied to sector 2–8 crops; $pcGTAP_{j}$ = purchases from sector 33 by sector j from the GTAP 7.0 database; $totalpcGTAP$ = total purchases from sector 33 by sectors 1–12 from the GTAP 7.0 database; $nclasmanure^{e}_{j}$ = quantity of element e in non-confined livestock excrement from sector j; $totalnclsmanure^{e}_{j}$ = quantity of element e in non-confined livestock excrement from sectors 9-12; $GTAPoutput_{j}$ = value of output (US$) from sector j; $totalGTAPoutput$ = total value of output (US$) from relevant sectors. 3 Total element flows calculated for confined livestock excrement are distributed first among farm system types based the relative application of manure N in Bouwman and Boumans (2002).

4.3.5 Non-Processed Material Flows

The non-processed material flows included in the ESAM are summarised in Table 5.13. Note that rice and crop emissions are described in Section 5.7.1 and that material flows associated with below ground crop residuals and crops lost to animal pests in Section 4.3.1. Additionally, there is significant non-production biomass flows associated with forestry activities. Krausmann *et al.* (2008) estimate global felling losses in forests as 0.653 Pg dry matter in 2000, based on a calculated difference in total forest fellings and forest removals. As with other vegetation flows included in the ESAM, a C to dry matter content of 50 percent is applied. The associated flows of N, P and S are then determined from the stoichiometry of terrestrial

vegetation.[88] In a similar manner to crop production, forestry also leaves behind considerable quantities of non-processed belowground biomass, with the estimated global flows derived from Krausmann *et al*. (2008).

Herridge *et al*. (2008) provide estimates of biological N fixation for different agricultural systems, including extensive, uncultivated tropical savannahs used for grazing. The estimated rate of N fixation within croplands is around 31,000 Tg N for 2005, broken down by some 12 different crop types. Accounting for small changes in crop production between 2005 and 2004[89] produces a revised global estimate for croplands of 29,730 Gg. N fixation flows of 18,100 Gg N and 12,000 Gg N are also adopted, respectively for pasture and fodder legumes and extensive savannahs.

Humans are further responsible for introducing a relatively significant quantity of reactive N to the biosphere as a result of N fixation in internal combustion engines, where conditions of high temperature and pressure enable otherwise inert atmospheric N_2 to react with oxygen. Because N is also contained within fossil fuels and released during combustion, careful consideration is required to account appropriately for the total quantity of atmospheric N fixed during combustion. The total fossil fuel combustion emissions of NO_x, produced both directly from fuels and from N fixation, is estimated as 21 Tg N for 1990 (Galloway and Cowling, 2002). Taking account of relatively significant increases in world primary energy demand between 1990 and 2004 (OECD, 2004) this is estimated to be 27 Tg N. The proportion of emissions derived from N-fixation is then approximated by comparing the quantity of petroleum delivered to global transport activities (IEA, 2009a, 2009b) and the likely N content of that fuel, with the total quantity of N emissions estimated for transport (i.e. NO_x, N_2O and NH3), is reported in the EDGAR database. The resulting estimate is around 11,000 Gg N, or just over 35 percent of total NO_x emissions, leaving 16,700 Gg N released from the oxidation of N contained within fuels.

Kruasmann *et al*. (2008) calculate that nearly 2,500 Tg of biomass dry matter were consumed in human-induced fires during 2000. Assuming that this is approximately the same for the study year, and applying a ratio of C emissions released per Tg of biomass combusted from Ito and Penner (2004), total emissions from human induced fires are set as 1,215.9 Tg C. This flow is disaggregated into individual atmospheric C species based on the relative emissions

[88] Refer to Section 5.4.1.
[89] http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor, accessed 8 Dec 2010.

reported by Andreae and Merlot (2001) for forest/savannah burning. The emission flows are, in turn, disaggregated to environmental source stocks (terrestrial vegetation, litter/detritus, soil organic C) by applying the same approach as used for wildfire emissions.[90] The calculations of N and S emissions from human-induced vegetation fires are analogous to the calculations used for natural wildfires. Consideration is, however, given to the proportion of living vegetation that, while consumed by human induced fires or wildfires, is not combusted. The IPCC (1996) applies a relatively low factor for non-combustion during vegetation fires of around 10 percent, while the rates of non-combustion discussed by Ito and Penner (2004) are much higher. A rate of 15 percent is applied, generating a flow of 170.6 Tg C from terrestrial vegetation to the litter/detritus stock.

Finally, the flow of C resulting from CH_4 recovery at landfills is derived by taking the global estimates by Bogner (2003) for the period 1980–96, and extrapolating the data forward to the study year.

[90] Refer to Section 5.7.1.

Table 4.13 Summary of Non-Processed Material Flows

Process	Source stocks		Receiving stocks		GTAP Code	Sector Disagg. Scalar[1]
	Name	Flux[2]	Name	Flux[2]		
Crop Production						
Below ground residuals	C dioxide(Tg C)	-609	Litter/detritus C (Tg C)	609	1-8	$cropprod^{e}{}_{j} / totalcropprod^{e}$
	Soil inorganic N (Gg N)	-14,910	Litter/detritus N (Gg N)	14,910		
	Soil inorganic N (Gg P)	-1,110	Litter/detritus P (Gg P)	1,110		
	Soil inorganic S (Gg S)	-3,830	Litter/detritus S (Gg S)	3,830		
Crops lost to pests	C dioxide (Tg C)	-618	Vegetation C (Tg C)	618	1-8	N/A
	Soil inorganic N (Gg N)	-15,310	Vegetation N (Gg N)	15,310		
	Soil inorganic P (Gg P)	-1,150	Vegetation P (Gg P)	1,150		
	Soil inorganic S (Gg S)	-3,960	Vegetation S (Gg S)	3,960		
Emissions from crops	C dioxide (Tg C)	-52	C monoxide (Tg C)	6	1-8	$cropprod^{e}{}_{j} / totalcropprod^{e}$
	Soil inorganic N (Gg N)	-4,040	Volatile organic C (Tg C)	47		
	Carbonyl sulfide (Gg S)	-20	Ammonia/ammonium (Gg N)	4,040		
	Soil inorganic S (Gg S)	-140	Hydrogen disulfide (Gg S)	20		
			Dimethyl sulfide (Gg S)	140		
Forestry						
Below ground residuals	Vegetation C (Tg C)	-405	Litter/detritus C (Tg C)	405	13,100	$timbharv_{j}{}^{e} / totaltimbharv^{e}$
	Vegetation N (Gg N)	-4,540	Litter/detritus N (Gg N)	4,540		
	Vegetation P (Gg P)	-1,320	Litter/detritus P (Gg P)	1,320		
	Vegetation S (Gg S)	-4,240	Litter/detritus S (Gg S)	4,240		
Felling losses	Vegetation C (Tg C)	-345	Litter/detritus C (Tg C)	345	13	N/A
	Vegetation N (Gg N)	-3,870	Litter/detritus N (Gg N)	3,870		
	Vegetation P (Gg P)	-1,130	Litter/detritus P (Gg P)	1,130		
	Vegetation S (Gg S)	-3,620	Litter/detritus S (Gg S)	3,620		
Nitrogen fixation						
Croplands	Dinitrogen (Gg N)	-29,730	Other soil organic matter N (Gg N)	29,730	1-6, 8	N/A
Pasture & fodder legumes	Dinitrogen (Gg N)	-18,100	Other soil organic matter N (Gg N)	18,100	8-12	Sector 8: 0.1 Sectors 9-12: 0.9 x $(lsmanure_{j}{}^{n} / totallsmanure^{n)}$
Extensive savannas	Dinitrogen (Gg N)	-12,000	Other soil organic matter N (Gg N)	12,000	9-12	$lsmanure_{j}{}^{n} / totallsmanure^{n}$
Internal cmbstn engines	Dinitrogen (Gg N)	-10,170	N oxides (Gg N)	10,170	All	$cdGTAPpp_{j} / totalcdGTAPpp$

Table 4.13 Summary of Non-Processed Material Flows (Cont.)

Process	Source stocks		Receiving stocks		GTAP Code	Sector Disagg. Scalar[1]
	Name	Flux[2]	Name	Flux[2]		
Human-Induced Open Vegetation Fires						
	Vegetation C (Tg C)	-1,138	C dioxide (Tg C)	1,110	100	N/A
	Other soil organic matter C (Tg C)	-228	Methane (Tg C)	11		
			Carbon monoxide (Tg C)	88		
			Volatile organic C (Tg C)	11		
			Carbonyl sulfide (Tg C)	<0.1		
			Litter/detritus C (Tg C)	114		
			Other lithosphere C (Tg C)	32		
	Vegetation N (Gg N)	-12,760	Dinitrogen (Gg N)	3,940		
	Other soil organic matter N (Gg N)	-5,050	N oxides (Gg N)	3,770		
			N oxides (Gg N)	180		
			Ammonia/ammonium (Gg N)	2,090		
			Litter/detritus N (Gg N)	7,830		
	Vegetation P (Gg P)	-3,710	Litter/detritus P (Gg P)	4,630		
	Other soil organic matter P (Gg P)	-920				
	Vegetation S (Gg S)	-11,920	S dioxide (Gg S)	620		
	Other soil organic matter S (Gg S)	-2,210	Carbonyl sulfide (Gg S)	10		
			Litter/detritus S (Gg S)	13,500		
Fugitive Emissions						
Solid fuels	Natural gas C (Tg C)	-80	C dioxide (Tg C)	51	15	N/A
			Methane (Tg C)	29		
Oil and gas	Natural gas C (Tg C)	-102	C dioxide (Tg C)	49	16, 17	N/A
			Methane (Tg C)	54		
	Other lithosphere S (Gg S)	<-10		<10	16,17	N/A
Rice Agriculture						
	Other soil organic matter C (Tg C)	39	Methane (Tg C)	39	1	N/A
			C disulfide (Tg C)	<0.1		
				<0.1		
			Dimethyl sulfide (Tg C)	<0.1		
	Other soil organic matter S (Gg S)	-60	C disulfide (Gg S)	<10		
			Carbonyl sulfide (Gg S)	<10		
			Hydrogen disulfide (Gg S)	40		
			Dimethyl sulfide (Gg S)	10		
Methane Recovery at Landfills						
	Methane (Tg C)	-5	C dioxide (Tg C)	5	56	N/A

Notes: 1. $cropprod^{e}_{j}$ = total element e in crops and aboveground residuals for sector j; $totalcropprod^{e}$ = total element e in crops and aboveground residuals for all sectors; $timbharv^{e}_{j}$ = mass of element e in timber harvests by sector j; $totaltimbharv^{e}$ = total mass of element e in timber harvests; $lsmanure^{n}_{j}$ = total mass of N in livestock excrement from sector j; $totallsmanur^{e}_{n}$ = total mass of N in livestock excrement of all sectors; $cdGTAPpp_{j}$ = mass of C in emissions from petroleum products by sector j from GTAP Energy CO_2 accounts; $totalcdGTAPpp$ = total mass of C in emissions from petroleum products from GTAP Energy CO_2 accounts.

4.4 Summary

Figures 4.1–4.4 present the ESAM environment-economy material flow accounts for C, N, P, and S in a diagrammatic form. To enable this information to be viewed within a single page for each element, the 58 sectors within the GTAP classification are aggregated to 12 sectors (refer to Table C.3 of Appendix C for a concordance). Similarly, the environmental commodities are also aggregated into 29 stocks, with a concordance available in Table E.6 of Appendix E.

Note that four types of material flows are identified in each diagram: (1) processed material flows, (2) non-processed material flows, (3) net wastes, and (4) net stock changes and transfers. In terms of processed material flows, those depicted on the left-hand side of each diagram correspond to direct material inputs, while those on the right-hand side are residuals. The net waste type is included to account for net transfers of elements between sectors within wastes. These flows are derived by calculating the difference between waste production and waste use (recycling, reuse and treatment) for each sector. A flow on the left-hand side indicates that the relevant sector uses more of a particular waste than it produces, while a flow on the right-hand side indicates that a sector is a net provider of a waste to other sectors.[91] Without construction of a full PIOT for each element, it is not possible to depict the flows of C, N, S and P between sectors contained in economic commodities. Nevertheless, applying the Mass Balance Principle, for a given sector and element, the difference between the sum of flows of categories (1) and (3) on the left-hand side, and flows (1) and (3) on the right-hand side, must correspond to the *net* transfer of materials to that sectors contained in economic commodities plus any relevant stock changes (4).

[91] As the net waste flows are calculated for each type of waste included in the ESAM accounts, it is possible for a sector to have a net waste flow depicted on both the left- and right-hand sides.

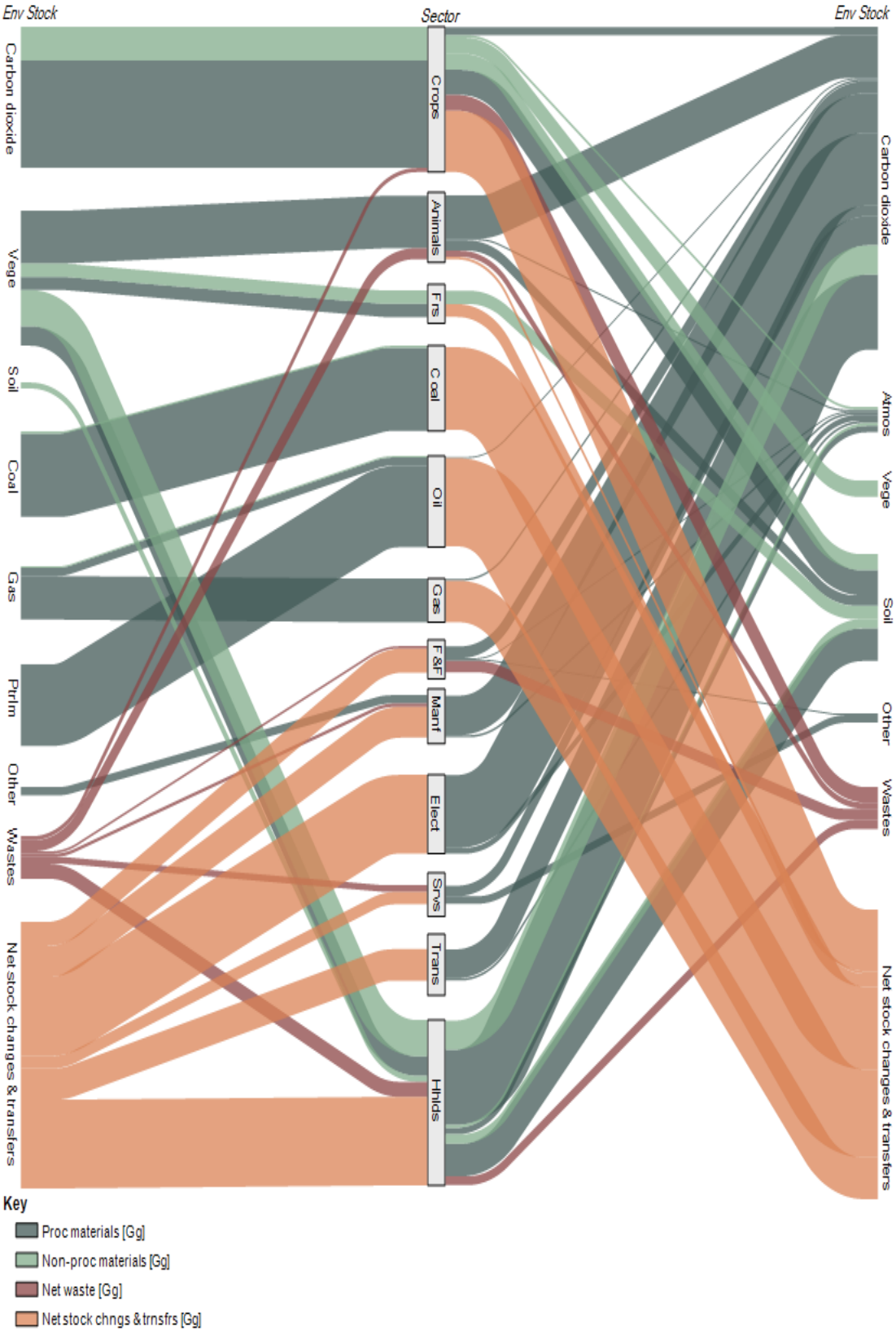

Figure 4.1 Anthropogenic Use and Supply of Global Carbon Stocks (Gg), 2004

Notes: Vege = Vegetation, Atmos = Atmosphere C other than CO_2, Ptrlm = Petroleum, Frs = Forestry, F&F = Food and fibre, Manuf = Manufacturing, Elect = Electricity, Srvcs = Services, Trans = Transport, and Hhlds = Households.

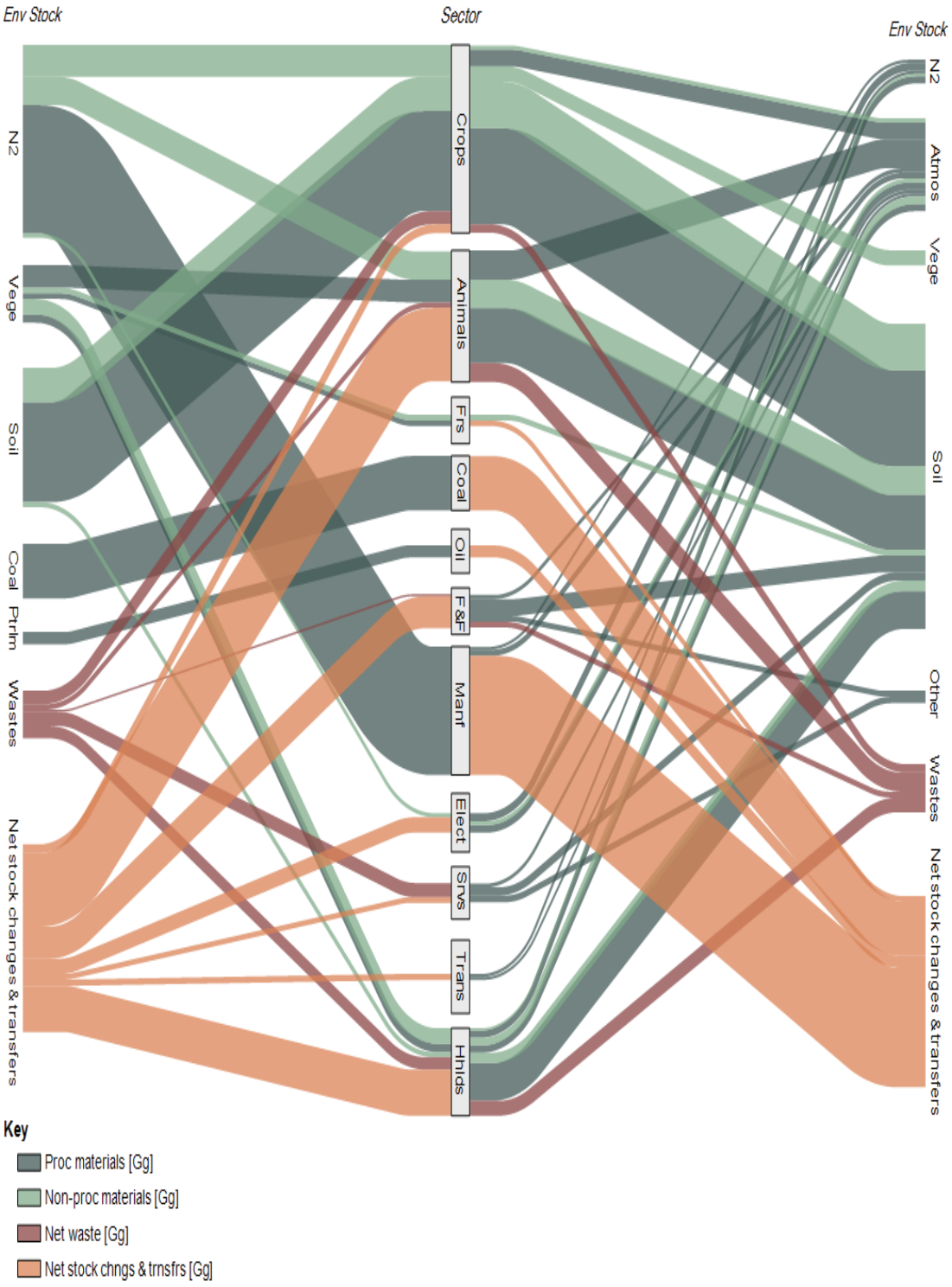

Figure 4.2 Anthropogenic Use and Supply of Global Nitrogen Stocks (Gg), 2004

Notes: N_2 = Dinitrogen, Vege = Vegetation, Atmos = Atmosphere N other than N_2, Ptrlm = Petroleum, Frs = Forestry, F&F = Food and fibre, Manuf = Manufacturing, Elect = Electricity, Srvcs = Services, Trans = Transport, and Hhlds = Households.

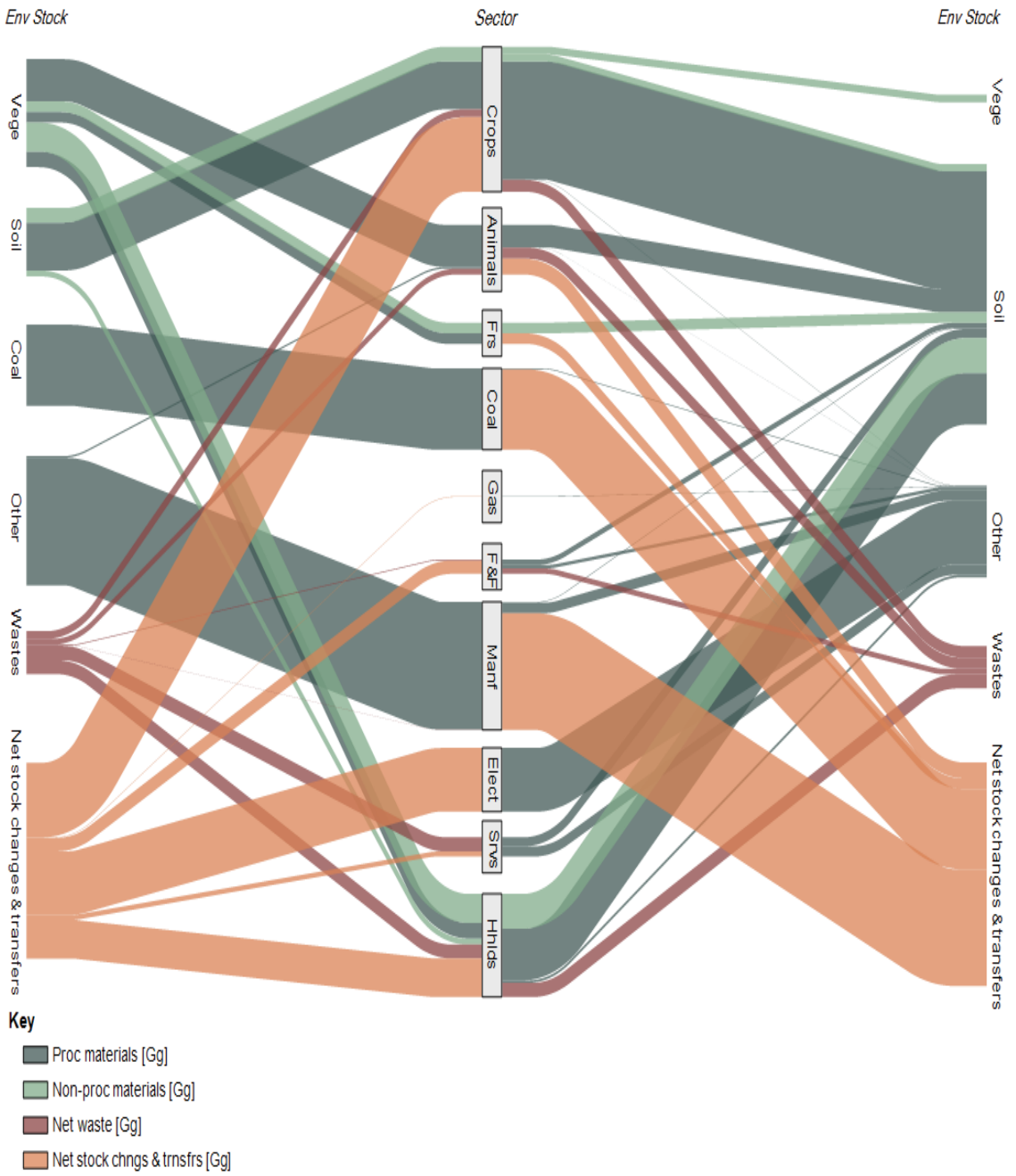

Figure 4.3 Anthropogenic Use and Supply of Global Phosphorus Stocks (Gg), 2004

Notes: Vege = Vegetation, Ptrlm = Petroleum, Frs = Forestry, F&F = Food and fibre, Manuf = Manufacturing, Elect = Electricity, Srvcs = Services, Trans = Transport, and Hhlds = Households.

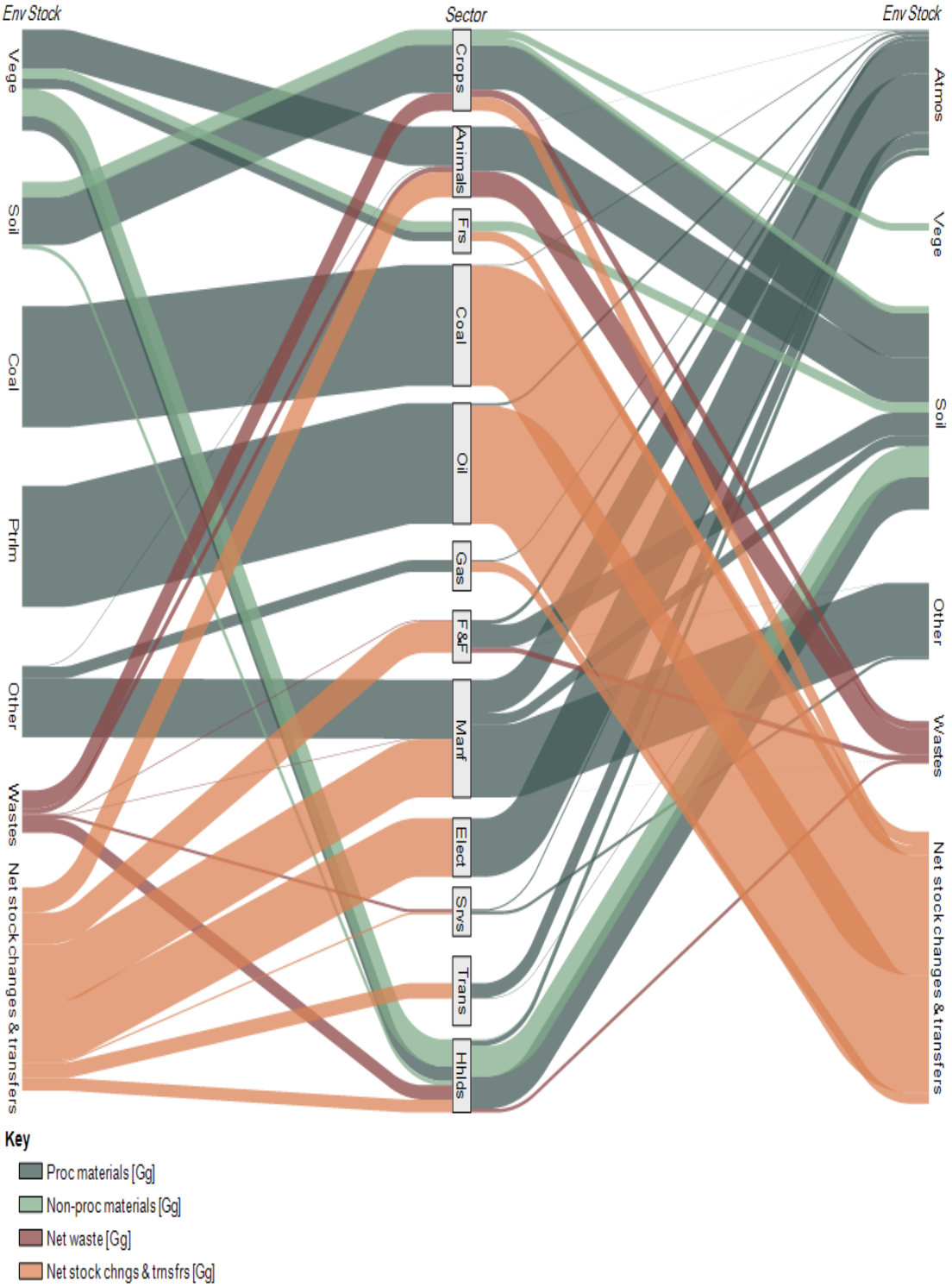

Figure 4.4 Anthropogenic Use and Supply of Global Sulphur Stocks (Gg), 2004

Notes: Vege = Vegetation, Atmos = Atmosphere, Ptrlm = Petroleum, Frs = Forestry, F&F = Food and fibre, Manuf = Manufacturing, Elect = Electricity, Srvcs = Services, Trans = Transport, and Hhlds = Households.

Carbon Material Flows

The flows of C through the global economy are dominated by a pattern of uptake of high-energy C commodities (biomass, fossil fuels) from the environment by primary industries, the net transfer of this C within economic commodities down production chains, and the subsequent release of low-energy C, predominantly as CO_2 emissions by manufacturing, services and final consumers (Figure 4.1). Going slightly against this pattern, the animals industry receives a very large input of high-energy C in the form of grazed biomass, estimated at nearly 2,000 Tg, with the net stock change and transfer flow for this industry only around 100 Tg. This occurs because of much of the biomass C required by the animals industry is returned to the environment, via animal respiration and excretion, by the industry itself. Furthermore, while some C is retained in the animal products sold to other sectors, these flows are partially offset by C contained within commodities purchased by the animals industry, e.g. livestock feed and energy commodities. Similarly, the crops industry takes significant quantities of low energy C from the environment, and produces a substantial net stock change and transfer flow. This is a consequence of the process of Net Primary Production (NPP) occurring within the industry itself.

Relatively substantial non-processed material flows are depicted for the crops industry. This is a result of biomass produced by the industry, but not used for economic purposes, e.g. lost to pests, belowground residuals. A substantial non-processed material flow is also depicted through the households sector. This amounts to 1,140 Tg C vegetation, and 114 Tg C of net soil lost via human-induced vegetation fires.

Nitrogen Material Flows

Figure 4.2 shows the immense scale of N flows associated with industrial N-fixation. This is represented by a flow of 128,000 Gg N_2-N into the manufacturing industry, balanced on the right-hand-side by an almost equivalent net stock change and transfer flow. Unlike the situation for C, the crops industry does not have a substantial net stock change and transfer flowing towards the right-hand-side of the diagram. The net stock change and transfer flow occurs on the left-hand side for the industry. This means that any N contained within crop products is more-than-compensated by the N contained in commodities consumed by the crop industry.

Anthropogenic fixation of N_2 to reactive N raises the energy state of that N, with the energy gradually dissipated as the reactive N is converted through a variety of forms, until it is

eventually denitrified back to N_2. In contrast to the C cycle, where the dominant form of anthropogenic residual is the most-stable CO_2 species, relatively little N is re-released from the economy directly as N_2. It is only during fossil fuel combustion that appreciable quantities of the gas are produced, estimated at around 19,600 Gg N. Substantial quantities of reactive N are, however, released into the atmosphere through production of other N residuals, particularly NO_x, 18,300 Gg N, and NH_4^+, 31,900 Gg. It is an unfortunate paradox that reactive N comprises a residual for many activities, while for agriculture it is demanded in vast quantities to support crop and pasture production. Although much of the reactive N released to the atmosphere occurs from dispersed fuel combustion (21,900 Gg), residuals burned in fields constitute a small source of reactive N (1,650 Gg) for which there is high potential for better utilisation.

Improving the management of reactive N emitted from livestock farming is important. Figure 4.2 depicts a residual flow from the animals industry to the atmosphere of some 30,100 Gg N, associated with manure emissions, coupled with a residual flow to soils of over 50,000 Gg N. If the coincidence of this reactive N in soils and N uptake by agricultural crops and pastures can be increased, this would greatly improve the efficiency at which reactive N is utilised in the production of economic commodities (Sutton and Billen, 2011). Interestingly, before the commercialisation of industrial N-fixation, livestock manure was the only major form of N fertiliser to croplands (Jarvis, 2011). Today, the transfer of N from animals to crops via manure is relatively small (depicted by the net waste flow to the crops industry in Figure 5.2). Significant potential also exists to better utilise N in other forms of wastes. The total N contained within global wastewater is estimated at some 45,600 Gg. Around 14 percent of this N is retained in sludge, 12 percent is released as emissions during wastewater handling, and the rest is otherwise disposed to the environment, often to waterways.

Phosphorus Material Flows

Similar to the N flows depicted above, anthropogenic P flows are characterised by a very large flow through the manufacturing industry (19,800 Gg), associated predominantly with fertiliser production. The significant size of the net sock change and transfer flow to the crops industry (11,500 Gg) also indicates that much of the P applied in fertilisers is lost from the economy almost immediately, i.e. without assimilation into economic commodities. Another noticeable feature of Figure 5.3 is the very large residual flow out of the electricity industry to the 'other' environmental stock category (9,860 Gg P). This is explained by the substantial production of coal ash P during electricity generation. Presently, the ESAM allocates coal ash P entirely as a

residual flow to landfills. However, given the magnitude of coal ash P production, it is important that the fate of this P at a global level is understood, including rates of reuse or recycling.

Unlike the case for N, the only major commercial source of P in fertiliser manufacturing is from mined lithosphere reserves. Over recent years, concerns associated with rising fertiliser prices, depletion of reserves, and the concentrations of reserves within a few nations, have focused greater attention on finding opportunities for improving P recovery, reuse and conservation (van Vuuren *et al*., 2010; Vaccari, 2011; Scholz and Wellmer, 2013)[92]. Vaccari (2011), for example, describes the technologies that could be employed to better recover P from wastewater, including treatment technologies, and separation of P wastes at source through use of urine diversion or no-mix toilets. The total P wastewater flow included in the ESAM is some 4,740 Gg, i.e. 24 percent of the P mining flow. Similar to the situation with N, there are significant opportunities to improve the reuse of P generated within animal excrement. Presently, of the animal waste that is collected from concentrated animal feeding operations and utilised as a fertiliser, much is applied in amounts beyond what can be assimilated by crops, resulting in excessive runoff (Vaccari, 2011). The total P contained in livestock P is estimated at some 4,570 Gg, with more than half produced from confined animals. There is also potential to utilise fly ash as a soil amendment (providing nutrients, reducing acidity, improving water retention) in crop production (Schoeman and van Deventer, 2004; Mittra *et al*., 2005; Basu *et al*., 2009). Due to radioactivity and heavy metal content, however, the current use of fly ash in agriculture is relatively limited (Basu *et al*., 2009).

Sulphur Material Flows

The largest raw material inputs of S to the economy originate from mined fossil fuels and minerals (Figure 5.4), respectively estimated at 64,300 Gg S, 64,100 Gg S and 37,600 Gg S for coal, petroleum and S minerals respectively. Although much of the fossil fuel S is combusted to atmospheric S, in a pattern similar to anthropogenic C flows, significant quantities are recovered from petroleum refining for use in industrial processes, particularly fertiliser manufacture. This helps explain the large net stock change and transfer flow depicted on the left-hand side for the manufacturing industry. Gypsum, produced as a by-product from industrial activities, is the ultimate destination for a huge proportion of the S passing through

[92] The estimated global reserves of PO_4^{3-} rock, as published by the USGS (2010, 2011) increased sharply from 16 Pg in 2010, to 65 Pg in 2011, largely due to increased estimates of Moroccan reserves. This has shifted the P debate away from a focus on scarcity, toward a focus on pollution (Edixhoven *et al*., 2013).

the economy. This is estimated at 38,900 Gg or 17 percent of all residual S flows. Similar to the situation with coal ash P, identifying and quantifying any major re-use or recycling flows for this residual would improve the S material flow accounts.

Chapter 5

Extended Material Flow Accounts of the Global Biogeochemical Cycles

5.1 Introduction

This chapter describes the population of the remaining physical accounts within the ESAM as specified under the framework set out in Figure 3.4. Specifically, these accounts are the 'within-environment' accounts, detailing the use and supply of environmental commodities by environmental processes (i.e. matrices $\tilde{\mathbf{A}}$ and $\tilde{\mathbf{B}}$ respectively), and the net change in environmental commodity stocks (i.e. vector $\tilde{\mathbf{q}}$).

The complete set of biogeochemical mass flow accounts for C, N, P, and S, integrating both the data from this chapter and Chapter 4, is found in Appendix D, Tables D.1-D.4.[93] For the within-environmental processes alone, more than 480 separate entries or biogeochemical mass flows are recorded.[94] When combined with the 'environment-economy' accounts of Chapter 4, which contain a high level of sectoral disaggregation, the result is a comprehensive and detailed static system model of the global biogeochemical cycles. The only other authors known to have produced similar sets of accounts or static models for global biogeochemical cycles are Costanza and Neill (1981) and Patterson (2002). Compared with the ESAM, however, the Costanza and Neill (1981) model is very coarse. Across all cycles, it captures only nine different processes, including economic processes, and nine different commodities.[95] While Patterson's (2002) model provides significantly more detail than the Costanza and Neill model, it notably records far fewer mass exchanges between the environment and economy compared to the ESAM. Unlike the ESAM, the Patterson model also does not contain a detailed sectoral breakdown for each environment-economy mass exchange.

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[93] In order to reduce space, the flows are combined into a single matrix of dimensions processes by commodities. Positive entries indicate the production of a column commodity by the row process (i.e. from matrix $\tilde{\mathbf{B}}$), while negative entries indicate the use of a column commodity by a row process (matrix $\tilde{\mathbf{A}}$). The environment-economy flows are aggregated into a single row at the bottom of the table. Full details are, however, available for these flows within Chapter 4.

[94] Many of the processes are aggregated for use in other parts of this thesis. Table B.5 maps processes between the various chapters of this thesis.

[95] Note, however, that unlike the ESAM, the Costanza and Neill (1981) matrices do include water-related processes and commodities. The Patterson (2002) model includes both water and energy-related processes and commodities.

When comparing the work undertaken in this thesis with previous contributions, it is also worth noting that numerous authors have documented components of the biogeochemical cycles in a way that is useful for compiling accounts such as the ESAM. This information, however, is not formalised in an IO, supply-use or other type of matrix structure. This chapter focuses on drawing together the vast range of information within the biogeochemical cycling literature into a comprehensive set of accounts. Another noticeable feature of the current biogeochemical cycling literature is, overall, a strong paucity of information on human-related mass flows. The ESAM fills this gap by providing a comprehensive coverage of both economic and environment-related biogeochemical mass flows.

The structure of this chapter is as follows: Section 5.2 provides a brief overview of the overarching principles and procedures employed in the construction of the accounts. A detailed summary of the specific methods and data sources relied on in calculating each of the individual cells or data points contained within the accounts follows. To provide some structure to the large set of information, Sections 5.3–5.6 begin by describing the major biogeochemical processes and commodity stock budgets, occurring *within* each of four different spheres – (1) atmosphere, (2) terrestrial biosphere, (3) oceans and (4) lithosphere. Section 5.7 then describes the biogeochemical processes responsible for mass exchange *between* these various spheres. Note that this structure represents a pragmatic approach to describing the biogeochemical cycles, as not all processes fit neatly into this categorisation.[96] Figures 5.1–5.4, which are also included in this chapter, provide a summary of the major biogeochemical mass flows for each cycle. [97] Note also that all C flows are recorded in Pg C, while the flows for N, P, and S are respectively recorded in Tg N, Tg P, and Tg S, and, finally, that all flow values are for the 2004 calendar year unless otherwise stated.

5.2 Production of Within-Environment Accounts

Construction of the within-environmental accounts for the biogeochemical cycles is laborious, requiring an iterative process of data triangulation involving numerous primary and derived datasets. There is, nevertheless, an overarching method adhered to in the construction of these accounts. In short, this involves establishment of a mass-balance account for each

[96] The process of NPP, for example, occurs within the terrestrial biosphere for the N cycle, but between the atmosphere and terrestrial biosphere for the C cycle.
[97] Figures 5.1–5.4 account for >98 percent of all mass flow in each cycle.

individual environmental commodity. Following the Mass Balance Principle, we know that for any particular commodity *m*, the total supply of that commodity by both economic and environmental processes, must be equal to the use of that commodity by economic and environmental processes, plus any net changes in the stock. Thus, repeating Eq. 3.7 within Chapter 3,

$$\sum_j \tilde{r}^p_{m,j} + \tilde{r}^h_m + \sum_n \tilde{a}_{m,n} + \tilde{q}_m = \sum_j \tilde{w}^p_{j,m} + \tilde{w}^h_m + \sum_n \tilde{b}_{n,m} \ . \quad (5.1)$$

Note that the mass flows for $\tilde{r}^p_{m,j}$, $\tilde{r}^h_m$, $\tilde{w}^p_{j,m}$, and $\tilde{w}^h_m$ are supplied directly from the accounts in Chapter 4. Of the remaining unknown mass quantities within the equation, one is selected as balancing item.[98] All other quantities can then be determined simply by taking the best available estimates from the literature.

There are, however, a number of additional constraints that must be taken into consideration in determining the appropriate mass flows. First is the requirement for mass balance not only across each commodity, but also across each process. In practice, this means simply that an increase in a commodity stock brought about by a particular process must be balanced by an equal reduction in another commodity stock (or stocks) by that same process. Hence for a particular processes *m*, an $\tilde{a}_{m,n}$ flow for one commodity is always balanced by another $\tilde{b}_{n,m}$ flow for another commodity. The second important constraint relates to ensuring consistency across the various element cycles considered. For a number of different types of environmental commodities, a set element ratio or 'stoichiometry'[99] is either available or can be determined from the literature. The derived changes in stock for that commodity must then adhere to this specified stoichiometry. For example, with a selected stoichiometry for terrestrial vegetation of 89 Pg of C for every 1 Pg of N, a net change in the terrestrial vegetation C stock of 0.6 Pg implies a net change of 6.7 Tg in the terrestrial vegetation N stock.

5.3 The Atmosphere

Over geological time, the atmosphere has experienced significant variation in composition, reflecting important changes in biogeochemical processes. Today, N and oxygen make up 98

[98] Occasionally more than one balance flow is selected for a particular commodity.

[99] Refer to Sterner and Elser (2002) for an interesting overview of the importance of the concept of stoichiometry in helping to understand ecological systems.

percent of total atmospheric mass. The remaining trace gases are mostly produced via biological processes, particularly microbial activities. In addition to gaseous molecules, the atmosphere contains various aerosols. These arise from, for example, wind erosion of soil minerals, the production of sea salt aerosols, and formation from pollutant emissions (Schlesinger, 1997). The global P cycle is different from the C, N, and S cycles in that no major component of the cycle involves gaseous substances. Phosphine gas is produced only under specific local conditions (Dévai *et al*., 1988). Nevertheless, quantities of P pass through the atmosphere via soil dust and sea spray.

5.3.1 Atmospheric Carbon

Although the concentration of C species within the atmosphere is relatively small, the importance of these gases cannot be overlooked, as is evidenced by current research on global climate change. The primary form of C in the atmosphere is CO_2, constituting over 99 percent of atmospheric C (Keeling *et al*., 1989). As well as CO_2, the ESAM identifies three other major forms of atmospheric C, carbon monoxide (CO), methane (CH_4) and an aggregate group of Volatile Organic Compounds (VOCs) including alcohols, aldehydes and organic acids. Additionally, there are three species of gas that exist within both the C and S cycles in the ESAM: carbonyl sulphide (OCS), carbon disulphide (CS_2), and dimethyl sulphide (DMS, $(CH_3)_2S$). For convenience, these are discussed in sections pertaining to the S cycle, although at an element level they are fully accounted for in both the C and the S cycles.

The atmospheric components of the global C cycle essentially involve the stepwise reaction of gases from less stable species, to more stable species, with CO_2 the ultimate product. Figure 5.1 provides a summary of the major biogeochemical flows occurring within the C cycle. The CO_2 stock is heavily interconnected within the C cycle, containing a number of significant input and output flows. Interestingly, the only significant flow from within the atmosphere itself is CO oxidation.

Due to variations in the rate of C emissions to the atmosphere, and the rate at which these gases are converted to CO_2, C is accumulating in the atmosphere. The Fourth Assessment Report (AR4) produced by the Intergovernmental Panel on Climate Change (IPCC) (Denman *et al*., 2007) states that the rate of C accumulation within the atmosphere for the period 2000–05 was 4.1 ± 0.1 Pg C yr^{-1}. This value is utilised as a constraint in the construction of the ESAM,

requiring that the total stock change for CO_2 equals 4.1 Pg yr^{-1}, less the stock changes assigned to other atmospheric C gases.

The annual stock change for CH_4 is calculated as the imbalance between sources and sinks as reported in the AR4 (1 Tg CH_4). Unfortunately, the AR4 does not contain a similar budget for CO. The Third Assessment Report (TAR; Prather *et al*., 2001) notes, however, that evidence suggests the global stock of CO was slowly increasing until the late 1980s, but has been decreasing since then, possibly due to reductions in automobile emissions (Zander *et al*., 1989; Bakwin *et al*., 1994; Khalil and Rasmussen 1994). Specifically, Khalil and Rasmussen (1994) estimate atmospheric CO decreased at a rate of 2.6 percent per year over the period 1988–92. Assuming this rate still applied in 2004, and a total stock value of around 0.15 Pg C (Prather *et al*., 2001), this equates to a net decrease in the CO stock of 4.0 Tg C yr^{-1}. Finally, the annual accumulation of VOCs within the atmosphere is set to zero. These gases have short atmospheric lifetimes (fractions of a day to months) and are thus quickly converted to more stable C forms (Prather *et al*., 2001).

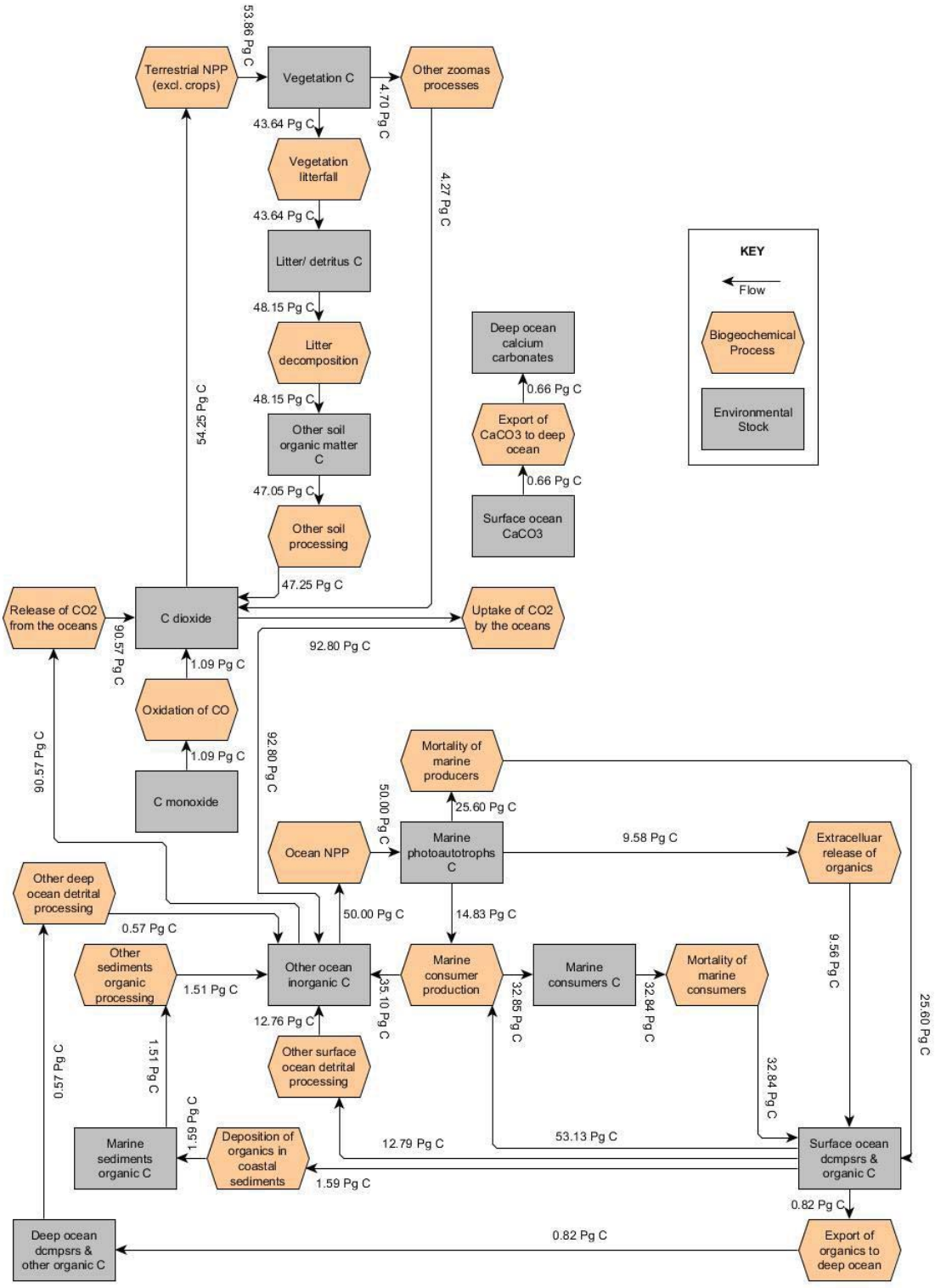

Figure 5.1 Environmental Biogeochemical Flows in the Carbon Cycle

In order to achieve the adopted rates of atmospheric C accumulation of C species (i.e. CO_2, CH_4, CO and VOCs), balancing flows are selected for each atmospheric C stock. For CO_2, the

selected balance flow is litter and soil respiration [**C56**][100]. In the case of CO, there are two primary atmospheric sinks for the gas- atmospheric oxidation to CO_2 [**C60**] and uptake by soil [**C56**]. Both flows are used as balancing items, totalling 1.33 Pg C, with 1.09 Pg allocated to the oxidation flow and 0.23 Pg for soil uptake (Schimel *et al*. 1995b). A similar approach is used for balancing the CH_4 stock. This time, however, there are three primary sinks for the gas reported in the AR4: oxidation by hydroxyl radicals in the troposphere, removal within the stratosphere and soil uptake [**C56**]. The first two processes, which both produce CO as a product, are aggregated to a single process within the ESAM [**C59**]. The calculated differences between the estimated sources of CH_4, and the adopted rate of net accumulation, is allocated to the sink flows on a pro-rata basis, using shares derived from the AR4 CH_4 budget (Denman *et al*., 2007). There are two major sinks for atmospheric VOCs- oxidation to CO [**C62**] and oxidation to CO_2 [**C63**]. Based on the value reported in the TAR, the ESAM incorporates a flow of 0.18 Pg C for oxidation to CO. The second flow is calculated as the balancing item for the VOCs stock, i.e. 0.43 Pg C.

5.3.2 Atmospheric Nitrogen

Although N is by far the most abundant element contained within the atmosphere, it is in a highly stable form (dinitrogen, N_2) under normal conditions, and thus unavailable to most organisms. The biosphere is, however, critically dependent on N fixation to convert N_2 into reactive species for biota. The only form of natural atmospheric N fixation is by lightning, where momentary conditions of high pressure and temperature allow N_2 to combine with O_2. The flow of N fixation by lightning is poorly understood, although it is estimated to be relatively small, with a range of 1.1–6.4 Tg N given in the AR4 (Denman *et al*., 2007). The ESAM adopts Galloway's (2005) value of 5.4 Tg N, derived from the earlier work of Lelieveld and Dentener (2000) [**N46**].

The atmospheric fixation of N_2 by lightning constitutes an input into the NO_x stock. This stock consists of an aggregation of two gas species, nitric oxide (NO) and nitrogen dioxide (NO_2), as well as atmospheric forms of the nitrate ion (NO_3^-). These species are strongly coupled in the atmosphere through redox reactions. Presently, there is limited information available on the total rate of accumulation of atmospheric NO_x, with spatial and temporal variations likely to be

[100]The code, [**C56**], enables the reader to match the key flows in this chapter directly with Tables D.1–D.4 of Appendix D. The reference [**C56**], for example, refers to process 56 'Other soil processing' within 'Table D.1 The Carbon Cycle Flows'. When no element symbol is contained within a reference, e.g. [**56**], this indicates that the process is recorded in all Tables D.1–D.4 of Appendix D.

significant (Denman *et al*., 2007). In any case, NO_x is likely to be a relatively unimportant sink for N within the global N cycle, as it is quickly scrubbed from the atmosphere via wet and dry deposition of NO_3^-. The ESAM therefore assumes a net rate of atmospheric accumulation of zero.

With a total atmospheric concentration of around 3.11 ppb (Trenberth and Guillemot, 1994), nitrous oxide (N_2O) pool of N is some 2.6 million times smaller than N_2. Nevertheless, it is a very important biogeochemical species, with each molecule of N_2O having the potential to produce around 300 times the Greenhouse Gas (GHG) effect relative to each molecule of CO_2, (Schlesinger, 1997; Denman *et al*., 2007). The ESAM adopts an absolute accumulation rate of 3.8 Tg N per year (Galloway, 2005). Due to the low reactivity of N_2O, the gas has a long life within the troposphere, and stratospheric destruction is the only significant sink (Jaffe, 1992; Schlesinger, 1997). The latter process [**N73**] is used as a balancing item in ESAM N_2O budget, with the total rate of stratospheric N_2O loss calculated as 14.2 Tg N.[101] Schlesinger's (1997) product ratios for N_2O destruction are adopted, with 80 percent of the N_2O consumed assigned to the production of N_2, and the remainder to NO_x.

Another important N species is ammonia (NH_3). It is the primary gaseous base within the atmosphere (Jaffe, 1992), and thus will react with acids, either in a gas or aqueous form, to produce ammonium (NH_4^+) salts. NH_3 and NH_4^+ are grouped into a single stock within the ESAM. Reaction with the hydroxyl radical, producing both NO_x and N_2O, is a relatively minor sink for the stock [**N49**]. The conversion of NH_3 to N_2O via this process is set as 0.6 Tg N (Denman *et al*., 2007). The rate of NO_x formation is very uncertain, although likely to be less than 0.5 Tg N (Denman *et al*., 2007). A flow value of 0.3 Tg N y^{-1} is selected. Like NO_x, NH_3 and NH_4^+ have a relatively short lifetime, with the primary sink being wet and dry deposition. Again like the NO_x stock, the total rate of atmospheric accumulation is assumed to be relatively minor, and is set to zero in the ESAM.

[101] N_2O source flows within the ESAM equal 18.0 Tg N; a figure within the bounds of the top-down (i.e. 15.8–18.4 Tg N), and bottom-up (i.e. 8.5–27.7 Tg N), global source estimates reported in the AR4 (Denman *et al*., 2007).

5.3.3 Atmospheric Sulphur

There are six atmospheric S species contained within the ESAM: sulphur dioxide (SO_2), hydrogen sulphide (H_2S), the three C-S gas species already identified (CS_2, OCS and DMS) and SO_4^{2-} ions found in various aqueous and aerosol forms. Like the C cycle, the atmospheric components of the S cycle are characterised by stepwise reactions of gases from less stable reduced species, to more stable oxidised species. The final oxidation product is SO_4^{2-}, which is rapidly returned to the Earth's surface via wet and dry deposition. While the current rates of accumulation of atmospheric S species are poorly known, these values are likely to be very small when compared with other components of the S cycle (Holser *et al*., 1989; Dobrovolsky, 1994). For this reason, the rates of atmospheric accumulation for all atmospheric S stocks are simply assumed to be zero.

The transformation of SO_2 to SO_4^{2-} is the largest within-atmosphere S flow at 83.7 Tg S. This is derived by multiplying the total quantity of SO_2 source emissions adopted in the model by 80 percent; the proportion estimated to oxidise to SO_4^{2-} (Dooney *et al*., 2007). Atmospheric destruction of DMS [**S9**] is the second largest within-atmosphere flow. DMS oxidation is complex, with the gas reacting primarily with OH during the daytime, and NO_3 at night (Turnipseed and Ravishankara, 1993; Jensen *et al*., 1991; Wilson and Hirst, 1996). OCS is a minor product from oxidation, with an adopted rate of production of <0.1 Tg S (Barnes *et al*., 1994; Watts, 2000). For simplicity, it is assumed that DMS emitted to the atmosphere is oxidised directly to CO_2 and SO_2.

OCS is also produced within the atmosphere via the oxidation of CS_2 [**S8**]. In his CS_2 budget, based on the work of Chin and Davis (1993), Watts (2000) places the total sink of CS_2 due to reaction with OH at 0.48 Tg S. The other major sink included in this budget is net soil uptake, estimated at 0.31 Tg S [**S56**]. In the ESAM, these two flows are selected as balancing items for CS_2, and both are within the uncertainty bounds given by Watts (2000). According to Brimblecombe (2005), half the S oxidised in the atmosphere is transformed to OCS, with the remainder forming SO_2.

Turning now to sink flows for OCS, the adopted production of H_2S from OCS [**S11**] is 0.08 Tg S (Watts, 2000). In order to balance the S emitted to the OCS stock, it is assumed that all remaining OCS emitted to the atmosphere, not accounted for by either vegetation or soil uptake, is oxidised in the atmosphere to SO_2 [**S11**].

The final within-atmosphere S flow included in the ESAM is the oxidation of H_2S to SO_2 [**S10**]. This process is selected as the balancing item for the H_2S stock, with a total flow of 9.15 Tg S calculated.

5.4 The Terrestrial Biosphere

Two major categories of terrestrial organisms are often identified: primary producers (i.e. terrestrial vegetation) and secondary producers (i.e. heterotrophic organisms). Prokaryotes, which account for the vast majority of heterotrophic biomass, and fungi are included in the ESAM soil stocks. This leaves a residual heterotrophic organism stock referred to as zoomass i.e. animals.

For each element, two organic soil stocks are identified: litter/detritus and other soil organic matter. The litter/detritus stock consists of fresh inputs of organic matter, predominantly plant debris, in and on the upper layers of the soil profile. The other soil organic matter stock is an aggregation of all other organic matter including soil organisms. In the global biogeochemical cycling literature, there is limited information upon which to separate freshwater organic and inorganic C, N, P and S, from other terrestrial reservoirs. Thus, the ESAM soil stocks include freshwater.

5.4.1 Net Terrestrial Primary Production (Excluding Agricultural Crops)

Net primary production (NPP) is the key integrative process in ecosystems (McNaugton *et al.*, 1989). It is the outcome of numerous interactions among elements, organisms, and the environment. Through terrestrial NPP, the energy required to drive all terrestrial biotic processes is ultimately derived, including the energy required by trophic webs sustaining animal populations and by decomposer organisms recycling nutrients within the soils. This pattern is evident in the mass flows depicted in Figure 5.1. C assimilated by plants from the atmosphere passes into zoomass and soil stocks where, following provision of metabolic energy, it is then returned to the atmosphere.

While for the C cycle NPP constitutes a major flow between the atmosphere and the terrestrial biosphere, for the remaining cycles, NPP involves predominantly a transfer of elements within the terrestrial biosphere itself. Figure 5.2 shows clearly shows the fast cycling of N within the

terrestrial biosphere. N is taken up by vegetation, subsequently expelled as litter, decomposed to soil organic matter and then soil inorganic N, and, finally, re-absorbed by vegetation. Analogous cycling loops are also depicted in the summary diagrams for P and S (Figures 5.3 and 5.4).

NPP is typically defined with reference to the C cycle. Chapin and Eviner (2005), for example, define NPP as the net C gain by vegetation over a particular period, usually a year, and is the balance between C gained by photosynthesis and the C released by plant respiration. Importantly, NPP is measured not only by the 'new' biomass produced by plants, but also by the soluble organic compounds that diffuse or are secreted by roots into the soil, the C transfers to microbes, and the emissions lost from leaves (Clark *et al*., 2001). In the ESAM, NPP includes flows of N, P and S, as the supply of these nutrients is also critical to this process.

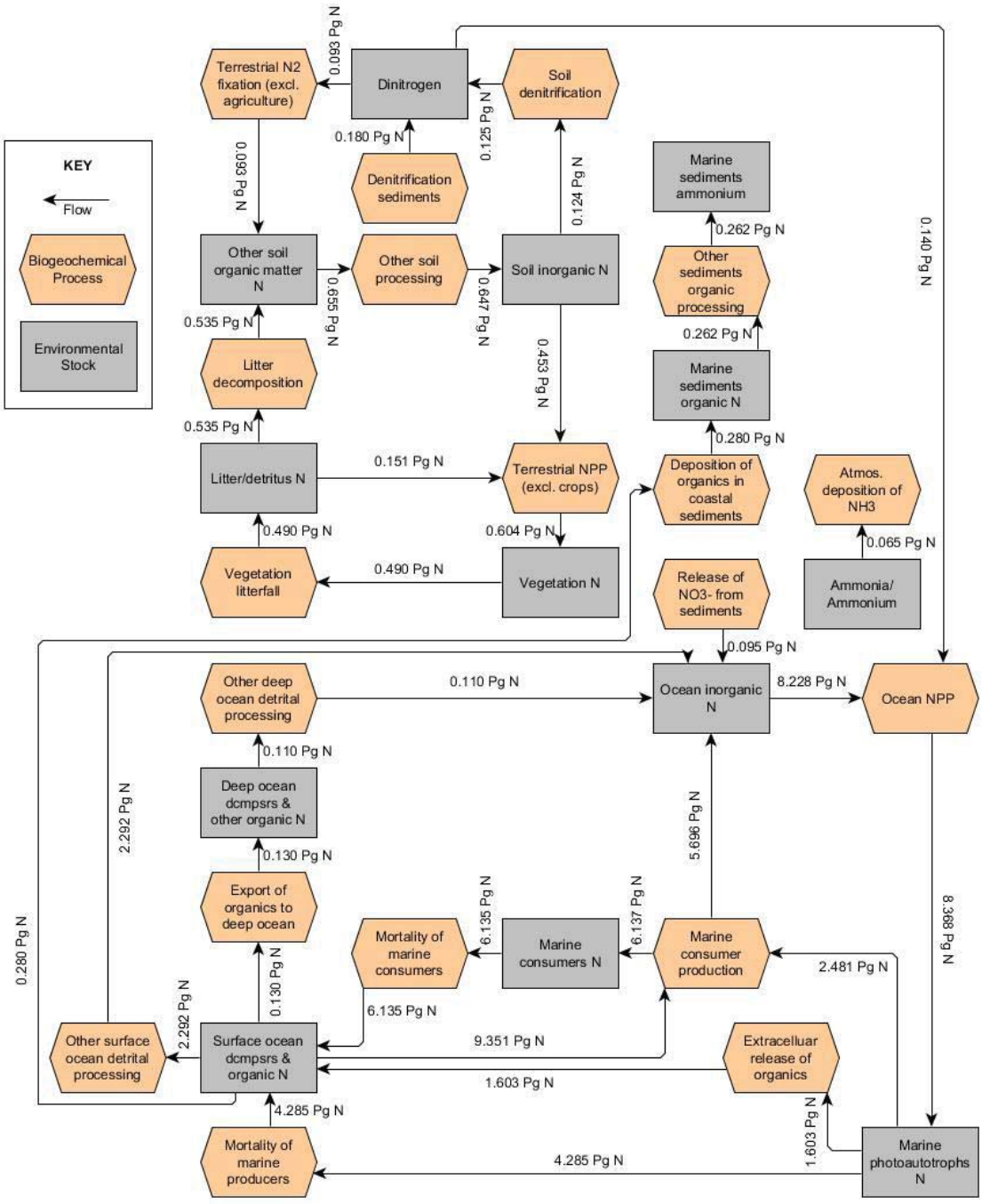

Figure 5.2 Environmental Biogeochemical Flows in the Nitrogen Cycle

Estimates of the global rate of C processed by NPP [**C76**] are relatively constrained (refer to Table 5.1). The ESAM adopts a flow value of 59.6 Pg C based on the model of Hazarika *et al*. (2005). The estimated total rate of NPP by crop vegetation is subtracted from this estimate, as this flow is accounted for within the environment-economy flows.[102] A small proportion of the C taken up by plants is returned to the atmosphere via gaseous emissions of CO and VOCs

[102] Refer to Section 4.3.1.

from plant foliage. This explains the small difference in Figure 5.1 between the mass of C removed from the CO_2 stock by NPP, and the mass of C delivered to vegetation via terrestrial NPP.

Table 5.1 Estimated Global Rate of Terrestrial Net Primary Production

Author	Terrestrial NPP
	Pg C yr^{-1}
This Study	59.6
Atjay (1979)	59.9
Esser *et al*. (1982)	63.0
Box (1988)	68.0
Houghton *et al*. (1990)	60.2
Hall and Scurlock (1993)	60.0
Melillo *et al*. (1993)	53.2
Potter *et al*. (1993)	48.0
Foley (1994)	62.0
Warnant *et al*. (1994)	65.0
Ruimy *et al*. (1996)	59.0
Field *et al*. (1998)	56.4
Amothor *et al*. (1998)	59.0
Potter (1999)	56.0
Saugier *et al*. (2001)	62.6
Hazarika *et al*. (2005)	59.6
Houghton (2005)	60.0

In order to account for the coupling of biogeochemical cycles through NPP, the ESAM utilises an estimate of the stoichiometry of terrestrial vegetation. Whereas the stoichiometry of marine primary producers is relatively settled (Redfield *et al*., 1963; Murray, 1992), estimates for terrestrial vegetation vary substantially. There are large stoichiometric differences among different types of plant tissues, different plant species and different biomes (Vitousek, 1982, 1984; Melillo and Gosz, 1983; Sterner and Elser, 2002). Table 5.2 provides a summary of the stoichiometry utilised by various authors. The ESAM adopts the stoichiometry of Bohlin *et al*. (1983), cited also by Chapin and Eviner (2005), of 790:7.6:1:3.1. Applying these ratios to the C flow for terrestrial NPP excluding crops, the estimated quantities of N, P and S assimilated into terrestrial vegetation are respectively 604 Tg, 176 Tg and 564 Tg.

We cannot assume that these values also represent the quantum of nutrients required for NPP. During the transition from live tissue to litter, plants resorb approximately half their leaf N and P in the process of senescence (Chapin and Kedrowski, 1983; Aerts, 1995; Aerts and Chapin, 2000), and around 35 percent of S (Quilchano *et al*., 2002). For other types of litter, the proportions of N, P and S resorbed are less significant (Chapin and Eviner, 2005). The adopted N, P, and S sorption rates for above ground litter are 25, 25 and 18 percent, respectively, while no resorbtion is assumed for below ground litter. Assuming also, based on the work of Millar (1974), Jensen (1984) and Sanderman and Amudson (2005), that 52 percent of total litter is foliage, 19 percent is other above ground litter and the remainder roots, a weighted average stoichiometry for plant litter is 1143.1C:7.6N:1.0P:3.5S.

The estimated flow of C from litterfall in non-crop vegetation [**C78**] is 43.6 Pg. When the vegetation and litter C:N ratios are applied to this flow, the difference in the two N values calculated provides an estimate of the total N resorbed during senescence. This is depicted in Figure 5.2 as a transfer of 151 Tg N from the litter/detritus N stock to vegetation N, via the process of NPP. Estimates of P and S resorbed can also be derived in a similar manner (Figures 5.3 and 5.4). On balance, the total mass of 'new' N, P and S required for NPP [**N76**, **P76**, **S76**] is respectively 453 Tg, 132 Tg, and 465 Tg. In the case of S, this initial estimate must be increased to account for S that is lost from vegetation via gaseous emissions of DMS and H_2S. The supply of N and P nutrients are treated as flows directly from the soil inorganic N and P stocks. S required for NPP is also derived from the inorganic soil stock; however, a small adjustment is necessary to account for the net uptake of OCS by vegetation.

Table 5.2 Reported Estimates for Terrestrial Vegetation Stoichiometry

Reference	Stock	C : N	C : S	C : P	N : S	N : P	S : P	Stoichiometry (mol of element: mol P)			
								C	N	S	P
This Study		104	255	790	2.5	7.6	3.1	790	7.6	3.1	1
Deevey (1973)	Vegetation	98	1470	882	15.0	9.0	0.6	882	9.0	0.6	1
Delwiche and Likens (1977)	Vegetation	128	638	510	5.0	4.0	0.8	510	4.0	0.8	1
Bowen (1979)	Vegetation							830			1
Likens *et al*. (1981)	Vegetation	121	686	2,057	5.7	17.0	3.0	2,057	17.0	3.0	1
Bohlin *et al*. (1983)	Vegetation	104	255	790	2.5	7.6	3.1	790	7.6	3.1	1
Vitousek *et al*. (1988)	Vegetation	180	3,351	3,404	19.0	18.9	1.0	3,404	19.0	1.0	1
MacKenzie *et al*. (1993)	Terrestrial biomass	60	62	200	1.0	3.3					
Schlesinger (1997)	Terrestrial biomass	160			0.4			160	1.0		
Elser *et al*. (2000)	Vegetation (foliage only)	36		968				968	26.9		1
Knecht and Goransson (2004)	Vegetation								22.1		1
Güsewell (2004)	Vegetation								27.6		1
McGroody (2004)	Vegetation (foliage only)	43		1,212				1,212	28.0		1
Ruttenberg (2005)	Terrestrial vascular plants	92		830				830	9.0		1

5.4.2 Zoomass Processes

From a stoichiometric perspective, animals are made up of specific types of biomolecules with associated element contents. Elser *et al*. (2000) give an estimate of the C:N:P molecular stoichiometry of herbivorous insects as 116.0C:17.8N:1.0P, while Sterner and Elser (2002) state that the typical C:N ratio of animals is 4-12. The adopted stoichiometry for terrestrial zoomass in the ESAM is 115.8C:14.5N:1.0P:0.2S.

The biomass created by NPP is available for heterotrophic consumption. Thermodynamic principles, however, place limits on the total material that can be converted into 'new' biomass by heterotrophs. The mass of C harvested by wild and domestic animals is around 11 percent of total NPP (Smil, 2002; Krausmann *et al*., 2008). Of this total, 1.93 Pg is allocated to grazing by domestic animals and 0.84 Pg to consumption of crops by animal pests.[103] The balance, refer to Figure 5.1, constitutes the flow of C from terrestrial vegetation to terrestrial zoomass [**C58**]. The values of N, P and S associated with zoomass consumption [**N58**, **P58**, **S58**] are then calculated as 61.1 Tg, 14.5 Tg, and 46.7 Tg respectively, based on the stoichiometry of terrestrial vegetation.

Smil (2002) estimates zoomass production as 0.40 Pg C, meaning that less than 10 percent of the total C consumed by zoomass is used in the formation of 'new' biomass. Assuming that the zoomass stock is in a steady state, the flow of C from terrestrial zoomass to litter resulting from zoomass mortality [**C45**] can be set as equivalent to the production flow. Applying the stoichiometry of zoomass, the respective N, S and P flows associated with terrestrial mortality [**N45**, **P45**, **S45**] are 58.3 Tg, 8.9, Tg and 1.9 Tg.

For each element cycle, the difference between the total mass consumed by zoomass, and the total mass taken up by secondary production, must be the mass returned to the environment via animal respiration and excretion. This means that the total C ejected by zoomass is 4.30 Pg [**C58**], of which 0.03 Pg is assumed to be CH_4 emissions by termites and other wild animals. The remainder is comprised of CO_2 respiration emissions, and C added to the litter/detritus stock from animal excretion or faeces. Limited information on the relative rates of zoomass respiration and excretion at a global level exists, thus the entire value is treated as a flow of C directly to the atmospheric CO_2 stock.

[103] Refer to Section 4.3.1.

The proportion of vegetation N consumed by zoomass, required for secondary production, is significantly higher than the proportion of C, reflecting the considerable drop in C:N ratios between terrestrial vegetation and zoomass. Overall, the total mass of N egested or excreted by terrestrial zoomass [**N58**] is calculated as 2.81 Tg, of which 0.12 Tg is assigned as a flow to atmospheric NH_3 (Bouwman *et al*., 1997). The remainder is treated as a flow to the litter/detritus stock. Similarly, the quantities of P and S ejected by terrestrial zoomass, 5.6 Tg [**P58**] and 44.8 [**S58**] Tg respectively, are calculated as the difference between consumption inputs and secondary production.

5.4.3 Litter and Soil Processing

Decomposition of organic matter within soils is a key biogeochemical process that roughly balances terrestrial NPP (refer to Figures 5.1–5.4). Communities of microorganisms (bacteria and fungi), often collectively referred to as microbes, predominantly undertake decomposition. The process is part of a complex food web in which biomass is continually consumed, decomposed, and reformed as 'new' soil biomass, along with the loss of energy and formation of secondary soil organic matter compounds. Given time and the right environmental conditions, almost all naturally occurring compounds can be mineralised completely to inorganic forms (Sanderman and Amudson, 2005).

In addition to the zoomass mortality and egestion/excretion flows, the ESAM identifies two non-anthropogenic inputs of organic matter to the litter/detritus stock: vegetation litterfall [**78**] and non-combusted material from wildfires [**80**]. In terms of magnitude, vegetation litterfall is the most significant, estimated at 43.7 Pg C or >90 percent of all organic C inputs to soils. This estimate is calculated as the difference between total inputs to the vegetation stock from NPP, and total losses due to zoomass consumption, wildfires and various anthropogenic processes, assuming that the stock of vegetation is increasing at a rate of 0.6 Pg C (Houghton, 2005). Applying the stoichiometry of litter[104], the N, P and S flows associated with litterfall can be calculated as 490 Tg, 142 Tg, and 457 Tg, respectively. It is assumed that the global litter/detritus stock is in an approximate steady state, and thus inputs to the litter/detritus stock, less that lost from wildfires and human induced fires, are balanced by microbial decomposition.

[104] Refer to Section 5.4.1.

In the process of decomposition, microbes take up C and nutrients to form 'new' microbial biomass. Decomposition is characterised by significant increases in the content of N and P of organic matter, relative to C content (Bohlin *et al*., 1983). Nearly all the CO_2 produced by soil respiration [**C56**] diffuses to the surface of the soil and escapes to the atmosphere, with only a small fraction dissolving into the soil (Edwards and Harris, 1977). In the ESAM, the mass of C released through soil organic matter respiration, but maintained within soils is derived simply by balancing the soil inorganic matter stock. Assuming that this stock is in an approximate steady state, and accounting for the quantity of C added to soils through weathering[105], an additional input of inorganic C from respiration of 0.03 Pg is required by soils to balance ocean export.[106,107]

A number of authors have put forward the proposition that the Earth's soils comprise at least part of a 'missing' terrestrial CO_2 sink, responsible for receiving C that would otherwise be found in the atmosphere. Unfortunately, current understanding of these sinks is relatively limited, and to date only a few attempts have been made to estimate the total rate of C accumulation within different terrestrial stocks including soils. Post and Kwon (2000) calculate that, using estimated rates of reforestation in the Northern Hemisphere, the rate of soil organic C accumulation may be around 0.11 Pg C. As this is also consistent with the value quoted in Houghton's (2005) global C budget, it is adopted as the net rate of soil organic C accumulation.

There appears to be even less information available on the rate of change in soil N, S, and P at a global scale, and how these changes in soil element stocks are distributed among organic and inorganic forms. For simplicity, the decomposition flows of N, S, and P from organic to inorganic forms [**N56**, **P56**, **S56**] are derived by treating these flows as balancing items for each of the respective soil organic matter stocks. The implication of this approach is that all net changes in soil N, S, and P, arising out of differences between identified soil sources and sinks, become assigned to the inorganic stock for each element. The respective rates of accumulation for soil N, S and P are $^{-}$69 Tg, $^{-}$67 Tg and $^{-}$4 Tg.

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[105] Refer to Section 5.7.5.
[106] Refer to Section 5.7.2.
[107] The other soil processing flow [**C56**] includes a small input to the inorganic C stock resulting from CH_4 uptake and oxidation.

5.5 The Oceans

5.5.1 Ocean Inorganic Flows

The world oceans contain around 60 times more C than the atmosphere, and 17 times more C than is stored in the terrestrial biosphere (Sarmiento and Gruber, 2006). When CO_2 is dissolved in seawater, it typically hydrates to form bicarbonate ions (HCO_3^-), as well as small quantities of carbonic acid (H_2CO_3) and carbonate ions (CO_3^{2-}). Together, dissolved CO_2, H_2CO_3, HCO_3^- and CO_3^{2-}, often termed Dissolved Inorganic Compounds (DIC), make up the other ocean inorganic C stock. Although the concentration of DIC varies between the surface and deep ocean, no attempt in the ESAM is made to partition ocean DIC into separate surface and deep ocean stocks. Taking account of all inputs to, and outputs from, global DIC, the ESAM calculates that this stock is increasing at a rate of 2.6 Pg C. This estimate can be compared to the rate of ocean C increase reported by Houghton (2005) of 1.8 Pg yr^{-1} and by Denman *et al.* (2007) of 2.8 Pg yr^{-1} for the 1990s.[108]

The ESAM also contains aggregate ocean stocks for inorganic N, P and S. As with C, the total rates of accumulation in the inorganic N and S stocks are calculated as the difference between the calculated sources to, and sinks from, each respective stock. Concerning P, the oceans are generally assumed to be in a steady state (Filippelli, 2002, 2008). This assumption is incorporated into the ESAM by setting the rate of P burial in ocean sediments as equal to the rate of P inputs from rivers and net atmospheric deposition.

5.5.2 Surface Ocean Producers and Consumers

Within the sunlit surface layers of the ocean, marine photoautotrophs utilise solar energy to convert dissolved inorganic matter (CO_2 and nutrients) into living tissues. Most recent estimates of the global rate of ocean NPP are between 45 and 60 Pg C (Table 5.3). The value applied in the ESAM is 50 Pg C [**C50**], as per the rate adopted in the AR4 (Denman *et al.*, 2007).

[108] The difference between Denman *et al.* (2007), and the ESAM, is that the latter adopts a higher rate of sediment C burial.

Table 5.3 Estimated Global Rate of Oceanic Net Primary Production

Author	Marine NPP
	Pg C yr^{-1}
This Study	50.0
Knauer (1993)	51.0
Hall and Scurlock (1993)	46.0
Mackenzie *et al*. (1993)	45.0
Longhurst *et al*. (1995)	48.3
Behrenfeld and Falkowski (1997)	48.0
Schlesinger (1997)	50.0
Field *et al*. (1998)	48.5
Yoder *et al*. (1998)	50.8
Houghton (2005)	48.0
Nakata and Doi (2006)	61.2
Denman *et al*. (2007)	50.0

Having determined a rate of C assimilation in ocean NPP, a stoichiometric ratio for marine photoautotrophs can be employed to estimate the quantities of other inorganic nutrients consumed. The most well-known work on ecological stoichiometry is that produced by Alfred C. Redfield (1890–1983), who found the elements of C, N, and P in marine particulate matter to be related by constant atomic ratios of 106C:16N:1P (Redfield, 1934, 1942, 1958; Redfield *et al*., 1963). Although more recent observations suggest that the oxygen and hydrogen content of organic matter suggested by Redfield *et al.* (1963) may be too high, relatively few changes have been proposed to the original Redfield values (Murray, 1992; Elser and Hassett, 1994; Falkowski, 2005; Sarmiento and Gruber, 2006). The ESAM, based on the work of Murray (1992), applies a ratio of 108C:15.5N:1P for marine photoautotrophs and 103C:16.5N:1P for the marine consumer stock.[109] Additionally, a ratio of 1.3S:1P is assumed for both marine producers and consumers, derived from Falkowski (2005).

Applying the stoichiometry of marine photoautotrophs to the estimated NPP C flow, the rates of inorganic N, P and S consumed in NPP by marine photoautotrophs are estimated at 8,368 Tg, 1,182 Tg, and 1,607 Tg, respectively [**N50**, **P50**, **S50**]. Figure 5.3 provides a diagrammatic

[109] While marine consumer stock comprise higher taxonomic species (e.g. fish, whales), in addition to plankton, and there is some variation in the stoichiometry of these species (refer to Sterner and George (2000), Tanner *et al*. (2000)), it is phytoplankton that accounts for the majority of total marine consumer biomass (Smil, 2002).

summary of the P cycle. Interestingly, the total rate of P required for oceanic NPP is almost 7 times that required for terrestrial NPP. In the case of N and S, the mass requirements for oceanic NPP are also significantly greater than for terrestrial NPP (Figures 5.2 and 5.4). This contrasts the situation under the C cycle (Figure 5.1), where the quantity of C assimilated in oceanic NPP is actually less than that assimilated in terrestrial NPP. This reflects the significant proportion of woody biomass, comprising tissues of high C content, contained within terrestrial primary producers compared with oceanic primary producers. The oceanic inorganic stocks supply the required quantities of P and S for NPP. In the case of N, however, the nutrient sources are more complex. While the majority of N required for NPP is obtained from dissolved NH_4^+ and NO_3^- ions, marine phytoplankton are also able to fix N_2. A fixation rate of 140 Tg N is adopted, consistent with the rate reported by Gruber and Galloway (2008). This is shown in Figure 5.2 as a direct flow from the N_2 stock to marine photoautotrophs via the process of NPP.

The extracellular release of materials by phytoplankton is an important source of dissolved organic matter within surface ocean waters. Nakata *et al.* (2004) calculate that in the high latitude North Pacific Ocean, 18 percent of the C captured by NPP is lost through extracellular release, increasing to 20 percent in the sub-tropical North Pacific Ocean. The ESAM adopts a flow of 9.6 Pg C [**C33**]. Of the products released by phytoplankton, emissions of DMS [**C33**, **S33**] have received particular attention in recent years. This is because the diffusion of DMS through the sea surface to the atmosphere is thought to constitute the major S gas emission from the oceans, with the oxidation products of the gas subsequently playing an important role in the regulation of the global climate system. To be precise, DMS is not actually released directly from plankton, but rather a preliminary product, dimethylsulfoniopropionate, is discharged from cells (Vairavamurthy *et al*., 1985; Dacey and Wakeham, 1986; Nguyen *et al*., 1998). The ESAM records only the proportion of dimethylsulfoniopropionate/DMS produced and emitted to the atmosphere. The adopted flow is 24 Tg DMS (Kettle and Andreae, 2000).

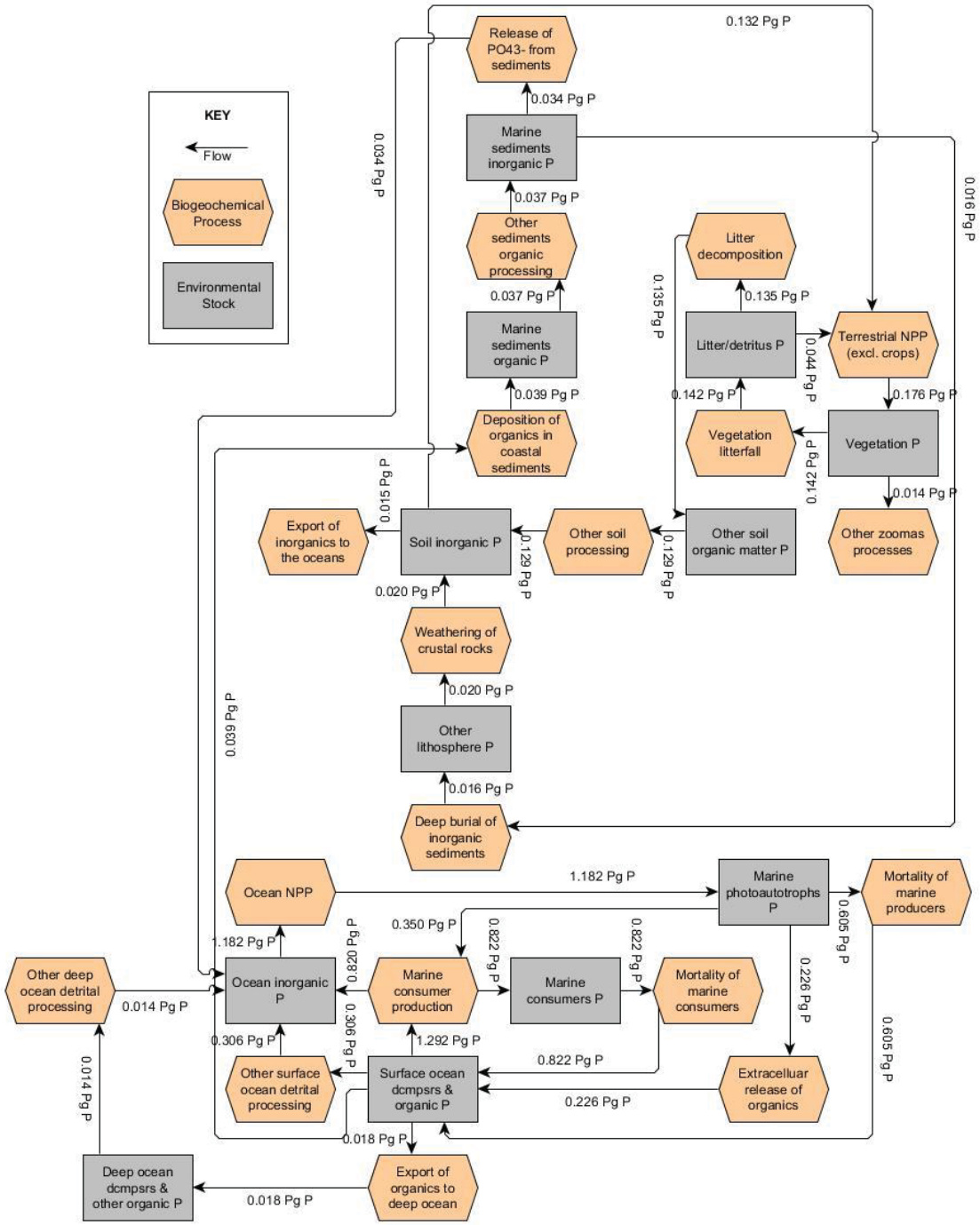

Figure 5.3 Environmental Biogeochemical Flows in the Phosphorus Cycle

Estimates of the share of ocean NPP consumed in secondary production vary substantially (Valiela, 1984; Landry and Calbert, 2004). With reference to the work of Nakata *et al*. (2004), this study assumes that 30 percent of total oceanic NPP, or 14.8 Pg C, is consumed by grazing zooplankton [**C42**]. Having accounted for the loss of C through extracellular release and grazing, the remainder of the C assimilated by marine producers through NPP, i.e. 25.6 Pg C, is set equal to the phytoplankton mortality flow [**C44**]. This approach implicitly assumes a steady

state for the global phytoplankton stock. Now, applying the stoichiometry of marine photoautotrophs, the consumption of marine photoautotrophs by zooplankton is calculated as 2,480 Tg N, 350 Tg P, and 476 Tg S [**N42**, **P42**, **S42**], while the mortality flow is calculated as 4,284 Tg N, 605 Tg P, and 822 Tg S [**N44**, **P44**, **S44**].

Again based on the work of Nakata *et al*. (2004), it is estimated that for every one unit of C supplied to consumers through phytoplankton grazing, 3.6 units of C are supplied from ocean organic matter [**C42**]. Applying the stoichiometry of Redfield, 106C:16N:1P, the mass of N and P taken up by marine consumers from organic matter stock is calculated as 9,351 Tg and 1,292 Tg, respectively [**N42**, **P42**]. Once again, applying Falkowski's (2005) ratio of 1.3S:1P, an associated estimate of the S flow [**S42**] is determined.

According to Nakata *et al*. (2004), around 52 percent of the total C consumed by marine zooplankton is returned to the surface ocean by respiration and excretion. Thus, out of a total input of 68.0 Pg C to the marine consumer stock, some 35.1 Pg C is allocated to respiration and excretion, leaving total net production as 32.9 Pg C [**C42**]. Without information on the relative inorganic and organic shares of respiration and excretion products, these are treated as a single input to the ocean inorganic C stock.

In addition to respiration and excretion, the major outputs from the marine consumer stock are global fish harvests and consumer mortality. With the rate of fish biomass harvests estimated at 0.01 Pg C, and assuming the consumer stock is approximately in a steady state, the rate of consumer mortality is set equal to the rate of consumer production, i.e. 32.8 Pg C [**C43**]. This equates to flows of 6,130 Tg N, 822 Tg P, and 1,106 Tg S, when applying the stoichiometry of marine consumers [**N43**, **P43**, **S43**].

Having determined all other inputs and outputs to the marine consumer stock, the rates of N, P, and S emitted by marine consumers through respiration and excretion can be estimated simply as a balancing item for each element i.e. 5,695 Tg N, 820 Tg P, and 1,108 Tg S from the marine consumer stock to respectively the N, P and S marine inorganic stock.

5.5.3 Organic Matter and Sediment Processing

For both the surface and deep ocean reservoirs, the ESAM contains an aggregate stock of particulate and dissolved organic matter referred to as ocean decomposers and other organic

stock. This stock receives organic matter from river discharge, dead and decaying organisms and partial remineralisation within sediments and phytoplankton extracellular release (Figures 5.1–5.4), and contains decomposer organisms that utilise this organic matter as a food source. Remineralisation acts on this stock in the opposite manner to photosynthesis, converting organic matter back into inorganic forms. While most remineralisation occurs within the surface ocean, quantities of particulate and dissolved organic matter are transported downward to the deep ocean, via particle settling and oceanic circulation. With the average residence time of particles in the upper mixed layer of ocean sediments being hundreds of years in continental margin sediments, and tens of thousands of years in deep ocean sediments, there is ample time for further sediment degradation (Martin and Sayles, 2005).

Table 5.4 presents a C budget for the oceanic organic C stocks. In order to estimate the flows of organic N, S and P associated with continental margin deposition [**N25**, **P25**, **S25**] and export to the deep ocean [**N31**, **P31**, **S31**] the stoichiometry for surface ocean organic matter (106C:16N:1P:1.3S) is simply applied to the relevant C flows, i.e. [**C25**] and [**C31**]. In the case of organic C exported into the deep ocean and deposited onto deep ocean sediments [**N26**, **P26**, **S26**], however, it is considered more appropriate to apply a stoichiometry of 117C:16N:1P (Anderson and Sarmiento, 1994) to the relevant C flow i.e. [**C26**]. The rate of burial of organic N in sediments [**N21**] is further derived from the associated C flow, this time applying a molar stoichiometry of sediments of 200C:14N (Schlesinger, 1997).[110] Note also that the total remineralisation flows of organic N, P and S within the surface [**N24**, **N57**, **P24**, **P57**, **S24**, **S57**] and deep ocean [**N22**, **N53**, **P22**, **P53**, **S22**, **S53**] are calculated simply as balancing items, assuming the stocks of decomposers and other organic matter are in a steady state.

Although the primary products of remineralisation are dissolved inorganic forms of each element, the ESAM does include a number of other minor products. These are primarily gases that diffuse out of the ocean into the atmosphere.[111] The process of denitrification is the most common form of anaerobic remineralisation within the water column, and is identified separately from other remineralisation processes.[112] Denitrification involves the use of NO_3^- as an oxidant, and the subsequent release of N_2 and N_2O. The ESAM adopts Gruber's (2004) estimate for total oceanic denitrification [**22**,**23**,**24**] of 65 Tg N. Note, however, that the global

[110] The total rate of inorganic N burial in sediments, [**N20**], is 10 Tg N. This is calculated by taking the total rate of N burial of 25 Tg N (Gruber and Galloway, 2008) and subtracting the organic N burial.
[111] Refer to Section 5.7.3.
[112] This explains why Table 5.4 identifies two remineralisation processes for each organic matter stock.

rate is very uncertain, and could be as much as double this value (Schlesinger, 1997; Codispoti *et al*., 2001; Galloway, 2005).

Table 5.4 Environmental Organic Matter Remineralisation, Export, and Deposition Flows

Stock	Biogeochemical Process	Code	Flow
			Pg C yr^{-1}
Surface Ocean Decomposers and Other Organic C Stock			
Inputs			
	Net release from marine photoautotrophs and consumers[1]	[C33,C42,C43,C44]	14.87
	River transport[2]	[C32]	0.38
Outputs			
	Export to deep ocean[3]	[C31]	0.82
	Net deposition to sediments[3]	[C25]	1.59
	Remineralisation[3]	[C24,C57]	12.84
Deep Ocean Decomposers and other Organic C Stock			
Inputs			
	Import from surface ocean[3]	[C31]	0.82
Outputs			
	Net deposition to sediments[3]	[C26]	0.24
	Remineralisation[3]	[C22,C53]	0.57
Marine Sediments Organic C Stock			
Inputs			
	Net deposition from surface ocean[3]	[C25]	1.59
	Net deposition from deep ocean[3]	[C26]	0.24
Outputs			
	Burial[3]	[C21]	0.17
	Remineralisation[3]	[C23,C55]	1.66

Notes: 1. Balance item. 2. Cole *et al.* (2007) and Seitzinger *et al*. (2010). 3. Derived from organic C budget of Sarmiento and Gruber (2006), with revised estimate of 'new' organic matter production in surface ocean (i.e. ocean NPP plus river transport) of 50.38 Pg C yr^{-1} (Denman *et al*., 2007; Cole *et al*., 2007; Seitzinger *et al*., 2010).

In terms of the denitrification products, Sarmiento and Gruber (2006) estimate total ocean N_2O emissions as 4 Tg N. Although a portion of this emission is likely to arise from water column nitrification along with sediment remineralisation, given the relatively small size of the flow it is simply assumed that all N_2O released from the oceans arises from denitrification within the water column. The remaining 61 Tg N produced from the process can then be assigned as a flow to the N_2 stock. Finally, the respective N_2O and N_2 emissions are split

amongst the surface [**N24**] and deep ocean [**N22**] denitrification processes based on the total N remineralised under each process. The associated flows of C, P, and S involved in denitrification are derived from chemical equations provided by Paulmier *et al*. (2009).

In addition to biogenic material produced in the water column, significant inputs of P to marine sediments arise from the downward settling of unreactive P entering the oceans via river transport and atmospheric deposition. The burial of inorganic P within marine sediments (Figure 5.3) constitutes one of only a few flows that are of sufficient magnitude to be included in the cycle summary diagram. The estimated rate of total P burial within continental margin sediments is 10 Tg P (Ruttenberg, 1993) and 10-13 Tg for deep sea sediments (Richey, 1983; Ruttenberg, 1993, 2005). In the ESAM total sediment P burial [**P20**, **P21**] is 22 Tg. Of total P buried, unreactive-P originating from rivers and atmospheric dust comprises 17.0 Tg (Section 5.5.3). Ruttenberg (1993) also estimates, based on Froelich *et al*. (1982), Ruttenberg (1993) and Colman and Holland, (2000), that some 25 to 30 percent is organic; the ESAM uses the midpoint of this range.

In terms of the S cycle, the major sink of inorganic S from the oceans is associated with the formation of pyrite minerals (e.g. Goldhaber, 2005). Sulphate-reducing prokaryotes (bacteria and archaea) use SO_4^{2-} as an electron acceptor for energy-generating organic matter oxidation, and release reduced S species into the environment. Assimilatory SO_4^{2-} reduction is widespread in ocean sediments, but is most important within continental margin sediments, where organic matter accumulation rates are greatest (Brimblecombe, 2005). Based on Mackenzie *et al*. (1993) and Schlesinger (1997), the adopted global rate of ocean sediment pyrite formation [**S29**] is 39 Tg.

Assuming a steady state for ocean sediment S, the difference between inputs of S to sediments through organic matter deposition, and outputs of S through pyrite formation, must equal the organic S either buried within sediments or remineralised. Given the paucity of information on global rates of organic S burial within ocean sediments [**S20**], it is assumed that the ratio of organic S buried to total sediment inputs of organic S is analogous to the N cycle. Thus, the adopted S burial flow [**S20**] is 4 Tg. The balance flow of 42 Tg S, assigned to organic matter remineralisation [**S23**, **S55**, **S70**], includes a denitrification flow of 6 Tg S and a H_2S emission flow of 0.8 Tg S.

5.5.4 Ocean Carbonate Cycle

The precipitation and sedimentation of ocean $CaCO_3$ are very important processes influencing global climate.[113] However, in comparison to other flows within the C cycle, the magnitude of these flows is quite small (Figure 5.1). A large number of marine organisms are responsible for precipitating $CaCO_3$ in their skeletal and protective tissues. Although shellfish are an obvious example, marine plankton and teleosts (bony fish) are also responsible for excreting carbonate precipitates (Wilson *et al*., 2009). The adopted global rate of $CaCO_3$ production [**C16**, **C17**] is 1.1 Pg C, taken from the mid-point of the range reported by Wilson *et al*. (2009).

Upon death of organisms, $CaCO_3$ particles fall through the water column and are either dissolved or deposited on sediments. As the surface of the ocean is over-saturated with respect to precipitated carbonate, much of the $CaCO_3$ formed within shallow water environments is preserved. The long-term accumulation of this material can result in the formation of extensive marine features, such as barrier reefs and carbonate platforms. Feely *et al*. (2004) estimate the net rate of $CaCO_3$ sedimentation within the coastal ocean as between 0.13 and 0.17 Pg C [**C48**]. Out of 'new' $CaCO_3$ produced within the surface ocean, it is also estimated that some 0.66 Pg C is exported to the deep ocean via sinking particles [**C29**] (Sarmiento and Gruber, 2006).

Until recently, it had been commonly thought that the dissolution of $CaCO_3$ particles occurred primarily at great depths, below the depth of calcite saturation (Broecker, 1977). However, recent analyses indicate that perhaps as much as 60 to 80 percent of the $CaCO_3$ that is exported out of the surface ocean dissolves in the first 1,000 m (Milliman, 1993; Milliman *et al*., 1999; Jansen *et al*., 2002). In the ESAM, the total rate of surface ocean dissolution of $CaCO_3$ is calculated as a balance item, assuming that the stock of $CaCO_3$ is in a steady state. The resulting flow of 0.44 Pg C [**C15**] is equal to two-thirds of the export flow.

[113] Rock weathering removes CO_2 from the atmosphere, producing both calcium and carbonate ions that are transported by rivers to the oceans. These are deposited through precipitation to the ocean floor where, following deep burial, they are converted into limestone. As weathering rates are increased by higher surface temperatures and atmospheric CO_2 concentrations, and greater inputs of carbonate to the oceans increases alkalinity and, thus, the area over which $CaCO_3$ is preserved and buried, these processes act as powerful regulatory mechanisms on atmosphere CO_2 concentration (Berner and Caldeira, 1997; Berner, 1999; Ridgwell and Zeebe, 2005). While precipitation of $CaCO_3$ is part of this long-term control on atmospheric CO_2, in the short term it has the effect of increasing atmosphere CO_2 concentration.

$CaCO_3$ that sinks into the deep ocean is subject to increasing under-saturation and thus will eventually dissolve. The depth at which dissolution is favourable is termed the calcite saturation horizon, and lies at around 4,500 m in the Atlantic, and 3,000 m in the Pacific. The ESAM incorporates a total flow to deep ocean sediments [**C12**] of 0.50Pg C, derived from Sarmiento and Gruber (2006). Total $CaCO_3$ remineralisation within the deep ocean [**C13**] is then calculated as a balancing item i.e. 0.20 Pg C.

Finally, to complete the discussion of the $CaCO_3$ cycle, consideration must be given to carbonate materials accumulated within marine sediments. Sarmiento and Gruber (2004) estimate that of the 0.50 Pg C of $CaCO_3$ deposited within deep ocean sediments, some 0.37 Pg is re-released back into the water column following sediment dissolution, and the remaining 0.13 Pg is buried [**C20**]. Unfortunately, the authors do not present a similar $CaCO_3$ budget for continental margin sediments. The net flow, [**C20**], of 0.15 Pg C, is derived instead from Feely *et al.* (2004).

5.6 The Lithosphere

Given the very long residence times of elements within lithosphere stocks, this reservoir often receives little attention within biogeochemical cycling literature. Similarly, in the ESAM, lithosphere processes are only crudely described. Four types of organic stocks are recognised: coal, petroleum, natural gas, and kerogen. The latter consists of the mixture of organic compounds found within sedimentary rocks. Aside from the special recognition given to carbonate minerals, all other lithosphere forms of each element are grouped together into a single aggregate stock.

An important lithosphere process is the transformation of kerogen into fossil fuels [**C37**]. Patzek and Pimentel (2005) report that the rates of petroleum and natural gas extraction are some 2.89 and 3.65 million times higher than the respective rates of formation for these fuels. This implies respective rates of formation of 1.0×10^{-6} Pg C and 0.6×10^{-6} Pg C. In the case of coal, Patzek and Pimentel (2005) report a formation rate of 7.5×10^{-6} Pg. This equates to 4.9×10^{-6} Pg C when multiplied by an estimated C content of 66 percent. Stoichiometry is used to convert the estimated rates of fossil fuel formation in C terms into other element flows. In the case of natural gas formation, which is comprised primarily of hydrocarbons, the element flows of N, S and P are considered negligible.

Apart from relatively small emissions of gases, the only other major sink process for kerogen included in the ESAM is its transformation during crustal subduction. Based on a total crust subduction flow of 36 Tg C (Dasgupta and Hirschmann, 2010), and crust composition information from Sundquist and Visser (2005), the loss of kerogen via subduction [**74**] is set as 6 Tg C.

5.7 Exchanges between the Spheres

5.7.1 Atmosphere and Terrestrial Biosphere Interface

The primary exchanges between the terrestrial biosphere and atmosphere occur as a result of biological processes (including primary production and soil processing), wildfires, aeolian emissions, and atmospheric wet and dry deposition.

Biological Flows

Through the process of primary production, biota exert a significant influence on the rate of chemical exchanges occurring between land and atmosphere. As noted in Section 5.4.1, the rate of CO_2 taken up by the biosphere through terrestrial NPP (excl. crops) [**C76**] is estimated as 54.2 Pg C. With the exception of CO_2 exchanges between the atmosphere and ocean, this is the single largest element flow recorded in the ESAM (Figure 5.1). These flows, along with various S gases absorbed or emitted by vegetation, are set out in Table 5.5. This table also covers zoomass emissions, and various terrestrial biosphere-atmosphere exchanges resulting from soil processing, including soil respiration, biological N fixation, and denitrification.

Wetlands

Emissions of trace gases from wetlands arise from similar biological processes to those discussed in the preceding paragraph. Nevertheless, wetlands are often given special consideration due to the high rates of atmospheric trace gas production. Usually emissions generated during rice cultivation are considered an anthropogenic flow, while emissions from other wetlands are considered non-anthropogenic. Rice agricultural emissions are reported in this section, but are included in the environment-economy accounts.[114] The adopted CH_4 emission from natural wetlands [**C18**], 0.14 Pg C, is derived from the average of estimates given by Wang *et al*. (2004), Mikaloff Fletcher *et al*. (2004), and Chen and Prinn (2006). By

[114] Refer to Section 4.3.5.

comparison, emissions from rice agriculture are set as 0.04 Pg C; derived from estimates given by Wuebbles and Hayhoe (2002), Wang *et al*. (2004), and Olivier *et al*. (2005). In terms of S species, Watts (2000) reports estimated flows of CS_2, OCS, H_2S, and DMS of 0.02 Tg S, 0.02 Tg S, 0.19 Tg S, and 0.06 Tg S, respectively. For each of these S emissions, the ratio of CH_4 emissions from natural wetlands to CH_4 emissions from rice agriculture is used to estimate the relative proportion arising from natural wetlands [**C54**, **S54**].

Aeolian Emissions and Wet and Dry Deposition

Atmospheric N oxides have a relatively short lifetime, as they react quickly with OH and are removed via wet and dry deposition (Prather *et al*., 2001). Similarly, atmospheric NH_3/NH_4^+ is short-lived within the atmosphere and usually deposited in precipitation and dry fall near point of origin (Schlesinger, 1997). The estimated rate of NO_x deposition to the oceans [**N4**] is 31 Tg N, while the assumed deposition rate of NH_3/NH_4^+ to the oceans [**N3**] is 19 Tg N. This means that a remaining NO_x deposition flow to land [**N4**] of 21.0 Tg N, and an NH_3/NH_4^+ flow [**N3**] of 33.3 Tg N, is required to balance the two atmospheric stocks. Applying a similar calculation, the adopted land deposition flow for PO_4^{3-} [**P5**] is 3.6 Tg P. This can be compared with a flow in the opposite direction of aeolian PO_4^{3-} aerosols [**P1**] of 4.3 Tg P (Ruttenberg, 2005). The estimated flow of SO_2 plus SO_4^{2-} from the atmosphere to land [**S6**, **S7**] is 87 Tg S, compared with an adopted aeolian emission flow [**S19**] of just 8 Tg S (Schlesinger, 1997).

Wildfires and Waste Disposal Sites

Taking an average of the values reported by Houweling *et al*. (2000) and Wuebbles and Hayhoe (2002), the CH_4 component of wildfire emissions [**C80**] is estimated at 2.6×10^{-3} Pg C. Based on Andreae and Merlot (2001) CH_4 emissions make up around 0.6 percent of the total C released during forest/savannah burning, and that CO_2, CO and VOCs emissions respectively make up the remaining 91.3 percent, 7.2 percent and 0.9 percent. Overall, total emissions of C from wildfires are thus calculated as 0.40 Pg C, or a little less than one percent of the non-anthropogenic flow of C from land to the atmosphere.

Table 5.5 Biological Flows at the Atmosphere and Terrestrial Biosphere Interface

	Description	Code	Stock	Flow	Units	Source/Comment
Fluxes from Atmospheric Stocks						
1	Uptake under NPP	[C76]	C dioxide	54.30	Pg C yr^{-1}	Hazarika *et al*. (2005).
		[S76]	Carbonyl sulfide	0.20	Tg S yr^{-1}	Watts (2000).[1]
2	Excretion of H_2S by vegetation	[S28]	S dioxide	0.05	Tg S yr^{-1}	Watts (2000).[1]
3	Terrestrial N fixation	[N75]	Dinitrogen	93.10	Tg N yr^{-1}	Derived from Boyer *et al*. (2004), includes adjustment for land use change and proportion of N fixation attributed to anthropogenic.
4	Other soil processing	[C56]	Methane	2.40	Pg C yr^{-1}	Hein *et al*. (1997), Weubbles & Hayhoe (2002), Wang *et al*. (2004) & Mikaloff Fletcher *et al*. (2004).
		[C56]	C monoxide	0.20	Pg C yr^{-1}	Schimel *et al*. (1995).
		[S56]	C disulfide	0.20	Tg S yr^{-1}	Calculated as a balance item for the C disulfide stock, within the range reported by Watts (2000).
		[S56]	Carbonyl sulfide	0.40	Tg S yr^{-1}	Watts (2000).
Fluxes to Atmospheric Stocks						
5	Volatile emissions from plants under NPP	[C76]	C monoxide	0.10	Pg C yr^{-1}	Prather *et al*. (2000).[1]
		[C76]	Volatile organic C	0.30	Pg C yr^{-1}	Total emissions from all plants estimated at 0.37 Pg C yr^{-1} for 1995 (Prather *et al*., 2000). Accounts for land cover change since 1995, and the proportion of emissions attributed to crops (Guenther *et al*., 1995).
		[C76]	Hydrogen disulfide	0.24	Tg S yr^{-1}	Watts (2000).[1]
		[C76]	Dimethyl sulfide	1.50	Tg S yr^{-1}	Watts (2000).[1]
6	Excretion of H_2S by vegetation	[S28]	Hydrogen disulfide	0.05	Tg S yr^{-1}	See flow 2.
7	Zoomass respiration and excretion	[C58]	C dioxide	4.30	Pg C yr^{-1}	Calculated as a balance item for the Zoomass stock.
		[N58]	Ammonia/ammonium	0.10	Tg N yr^{-1}	Bouwman *et al*. (1997).
8	Zoomass methane emissions	[C58]	Methane	0.03	Pg C yr^{-1}	Prather *et al*. 1995, Houweling *et al*. (2000), Weubbles & Hayhoe (2002), Mikaloff Fletcher *et al*. (2004), Wang *et al*. (2004) & Chen & Prinn (2006).
9	Soil denitrification[2]	[N72]	Dinitrogen	124.90	Tg N yr^{-1}	Galloway *et al*. (2004) gives an estimate of 115 Tg N yr^{-1} during the early 1990s, increasing to 158 Tg N yr^{-1} by 2050.
		[N72]	Nitrous oxide	5.70	Tg N yr^{-1}	Assumed one mole of N_2O-N released for every 22 moles of N_2-N (Schlesinger, 1997).
10	Other soil processing	[C56]	C dioxide	47.30	Pg C yr^{-1}	Calculated as a balance item for the C dioxide stock.
		[N56]	Nitrous oxide	5.50	Tg N yr^{-1}	Emissions for the 1990s from Denman *et al*. (2007) *less* changes in land cover less, denitrification (see flow 9) and emissions from storage/handling of manure.
		[N56]	Ammonia/ammonium	2.40	Tg N yr^{-1}	Denman *et al*. (2007).
		[S56]	Hydrogen disulfide	0.40	Tg S yr^{-1}	Watts (2000).
		[S56]	Dimethyl sulfide	0.10	Tg S yr^{-1}	Watts (2000).
11	NOx release from soils	[N68]	N oxides	8.00	Tg N yr^{-1}	Jaeglé *et al*. (2005).

Notes: 1. The share of crop NPP, out of total NPP, is used to calculate the proportion attributed to crops. 2. The soil flows of C, N, and P associated with denitrification are based on molar ratios provided in Paulmier *et al*. (2009).

The increase in atmospheric C resulting from forest fires must be balanced by an equal loss of C from the terrestrial biosphere. It is not just organic matter within live vegetation that is consumed during forest and savannah fires, but also woody debris and other litter, and soil organic C (Ito and Penner, 2004). There is a paucity of information on which to apportion C

among terrestrial source stocks. In the global C cycle presented by Houghton (2005), of the total amount of C lost from land through land use change, 77 percent is attributed to loss from vegetation, 5 percent from litter, and 18 percent from soils. As forest and savannah fires are a major component of the land-use change flow, it is assumed that Houghton's percentage shares are also reflective of the relative source contributions of C consumed in wildfires.

In addition to the primary C species emitted during wildfires, a number of trace N and S species are released. Based on the forest and savannah emission estimates presented by Andreae and Merlet (2001), it is estimated that for every 1 Pg of C released as CO_2, 3.6 Tg of N is released as N_2, 3.4 Tg as NO_x, 0.2 Tg as N_2O, and 2.2 Tg as NH_3. Applying these ratios to the above estimated CO_2 produced from wildfires gives a total flow of N gas species of around 3.6 Tg N [**N80**]. Emissions of SO_2 are similarly calculated according to the ratio of SO_2 to CO_2 emissions, as reported by Andreae and Merlet (2001), producing an estimated flow of 0.2 Tg S [**S80**]. In the case of OCS emissions, Watts (2000) reports a total flow from biomass burning of 0.04 Tg S. In the ESAM, this is apportioned among 11 different biomass combustion flows, both natural and anthropogenic, according to the relative CO_2 emissions calculated for each flow. Total OCS emissions from wildfires [**C80**, **S80**] are thus estimated at just 3×10^{-3} Tg S.

The final terrestrial biosphere-atmosphere flows are associated with emissions from waste disposal sites. Although these emissions are treated as occurring outside of the economy, the explanation of how these were generated is left to Chapter 4.[115] The total flow of CO_2 and CH_4 from landfills [**C27**] is estimated as 0.11 Pg C.

5.7.2 Terrestrial Biosphere and Oceans Interface

The flow of inorganic C from the terrestrial biosphere to the oceans is estimated as 0.45 Pg, comprising 0.26 Pg from river transport and 0.19 Pg from groundwater transport (Cole *et al*., 2007). With the input of particulate $CaCO_3$ to the oceans from land estimated at around 0.20 Pg C (Feely *et al*., 2004), the remaining 0.25 Pg delivered to the oceans is assumed to be DIC [**C30**]. Most estimates of the total land-ocean flow of organic C fall in the range of 0.30 to 0.55 Pg C (Schlesinger and Melack, 1981; Meybeck, 1988, 1993; Degens *et al*., 1991; Ludwig *et al*., 1996; Houghton, 2005; Cole *et al*., 2007; Seitzinger *et al*., 2010). The value incorporated into

[115] Refer to Section 4.3.3.

the ESAM [**C32**] is 0.38 Pg C, based on estimates given by Cole *et al*. (2007) and Seitzinger *et al*. (2010).

Human activities have drastically increased the rates of inorganic N transport in rivers through inputs of industrial fixed N to terrestrial systems (Galloway and Cowling, 2002; van Drecht *et al*., 2003). A group of frequently cited articles place river transport of inorganic N at around 20 Tg yr^{-1} for the 1990s (Galloway *et al*., 1995; Galloway and Cowling, 2002; Galloway, 2005; Gruber and Galloway, 2008), compared with an estimated flow of only 5 Tg yr^{-1} in the 1890s (Galloway and Cowling, 2002). Accounting for a further increase in the rate of inorganic N transport since the 1990s, the ESAM adopts a flow value of 21 Tg N [**N30**]. Note that the 1890 flow can be set as equivalent to the background weathering rate [**N79**] (Lavelle *et al*., 2005). Although most studies of river N transport concentrate on inorganic N, forms of organic N are also increasingly recognised to contribute to the total loss of N from terrestrial systems (Schlesinger, 2008). With recent estimates of the total river transfer of reactive N to the coast placed at around 60 Tg yr^{-1} (Boyer *et al*., 2006; Schlesinger, 2009), and subtracting the already identified proportion that is inorganic, the adopted organic N flow [**N32**] is 40 Tg.

Within terrestrial systems, P-sorption into soil particles maintains the P available for biological processes at low levels (Lajtha and Harrison, 1995). Most of the P transported by rivers is in this unreactive, particle form, which settles quickly onto coastal sediments and is re-buried. Due to the increased ionic strength of marine waters, however, a proportion of the particulate flow becomes reactive on entering the ocean (Ramirez and Rose, 1992; Berner and Rao, 1994; Ruttenberg and Canfield, 1994; Colman and Holland, 2000; Compton *et al*., 2000). The total particulate P flow adopted in the ESAM [**P30**, **P32**], 19.2 Tg P, and the proportion that is soluble, 35 percent or 6.7 Tg P, are both derived from the mid-point of ranges reported by Ruttenberg (2005). It is further assumed that 30 percent of the particulate P that becomes reactive on entering marine waters is organic (Meybeck, 1982; Ruttenberg, 2005). The transport of dissolved P in rivers also occurs in both organic and inorganic forms [**P30**, **P32**]. The adopted flow of dissolved organic P to the oceans is 0.6 Tg P, while the dissolved inorganic flow is 1.5 Tg P (Seitzinger *et al*., 2010).

Although the concentration of inorganic S is much less in freshwater compared with seawater, rivers are responsible for moving a large amount of dissolved SO_4^{2-} to the sea each year. Husar and Husar (1985) suggest a global flow of S from non-desert land to the oceans of 131 Tg S yr^{-1}. A more recent estimate, by Brimblecombe (2005) of total SO_4^{2-}, records transport as 225 Tg

S yr^{-1}. The latter estimate is adopted in the ESAM [**S30**]. A summary diagram for the S cycle is provided in Figure 5.4.

Information on the global land-ocean transfer of organic S is scarce. Applying a mass ratio for dissolved organic matter in freshwater of 43.1C:1S (Perdue and Ritchie, 2005) gives an estimated organic S flow [**S32**] of 9 Tg.

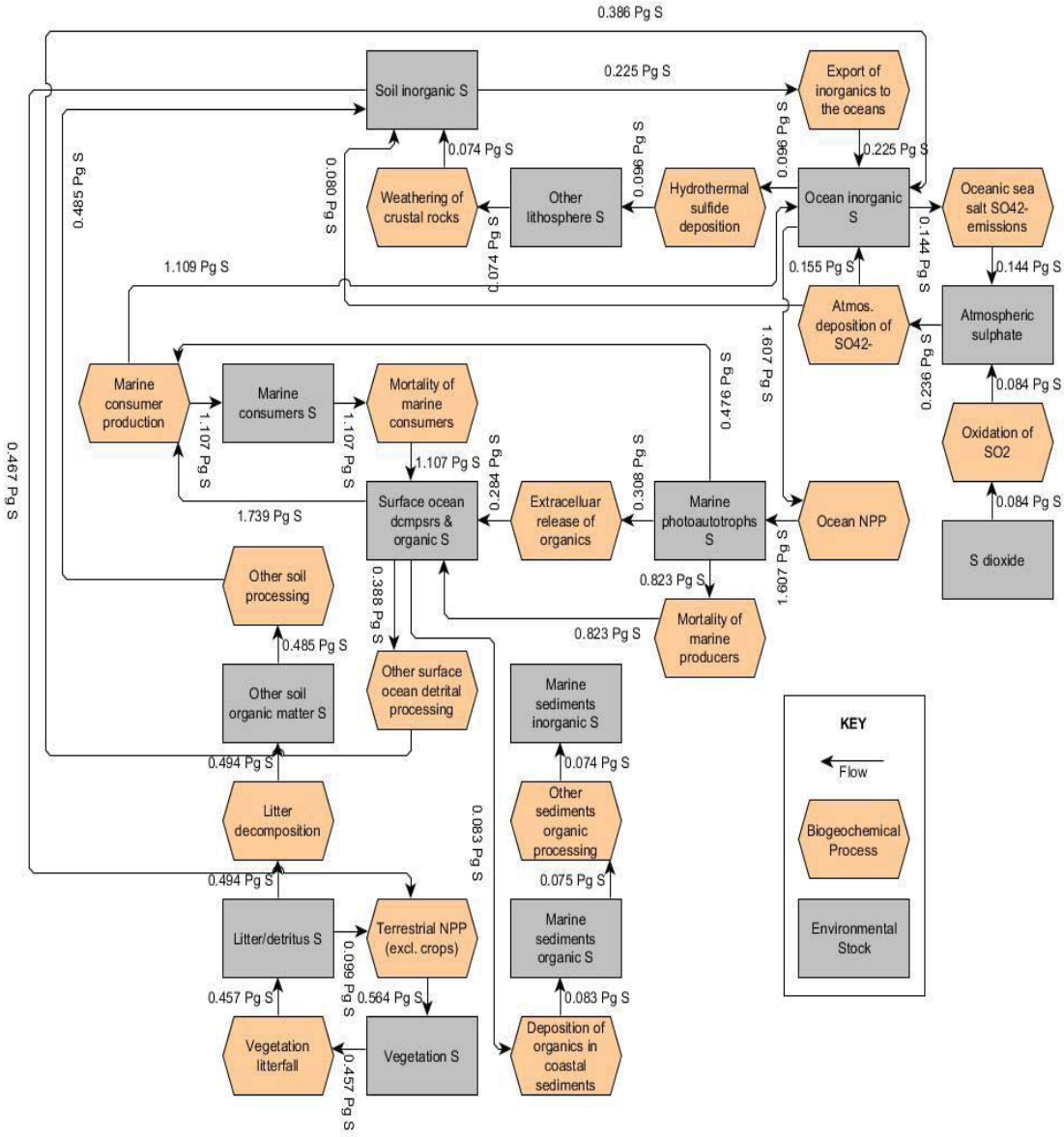

Figure 5.4 Environmental Biogeochemical Flows in the Sulphur Cycle

5.7.3 Ocean and Atmosphere Interface

Among the most processes for the modern-day C cycle is the exchange of inorganic C between the atmosphere and oceans, determined by the chemical equilibrium of DIC in the ocean (Sarmiento and Gruber, 2006). The current uptake of C by the oceans is estimated as 92.8 Pg, which is slightly greater than the C transfer occurring in the opposite direction (Figure 5.1), estimated as 90.6 Pg (Denman *et al*., 2007). As shown in Table 5.6, these flows comprise almost entirely exchanges of CO_2 [**C66**, **C77**], with the mass of C released as CO and methane from the oceans [**C57**] together totalling less than 0.1 Pg C. Other element exchanges between the atmosphere and oceans included in the ESAM, and the data sources from which these flows are derived, are also described in Table 5.6. Note that the table excludes N exchanges associated with denitrification and N-fixation, as these area covered in Sections 5.5.2 and 5.5.3.

5.7.4 Ocean and Lithosphere Interface

The primary exchanges occurring between the oceans and the lithosphere are the burial flows of organic and inorganic materials within sediments. These flows are used in estimating the rates at which various materials are re-released into the water column following sediment mineralisation and have been described in Sections 5.5.3 and 5.5.4. The only remaining ocean-lithosphere flows included in the ESAM are the hydrothermal processes leading to formation of $CaCO_3$ and sulfide deposits.

Hydrothermal vents in the deep ocean typically form along mid-ocean ridges at locations where two tectonic plates are diverging. At these locations, seawater drawn into the hydrothermal system is heated and mixed with upwelling magma. The ensuring hot hydrothermal fluids contain high concentrations of H_2S, which specialist communities of chemoautotrophic bacteria are able to metabolise, in conjunction with O_2 and CO_2 from deep-sea waters, to produce 'new' organic matter. Respired S produced by this reaction can accumulate into significant deposits at the ocean-lithosphere interface. Symbiotic bacteria within hydrothermal vent tube worms *Riftia*, for example, produce tubular columns of S up to 1.5 m long (Cavanaugh *et al*., 1981; Lutz *et al*., 1994). As shown in Figure 5.4, the estimated total loss of ocean inorganic S associated with hydrothermal vent processes [**S39**] is significant at 96 Tg (Schlesinger, 1997). Additionally, the global ocean $CaCO_3$ budget presented by

Sarmiento and Gruber (2006) reports a small exchange of carbonate from the lithosphere to the deep ocean of 0.04 Pg C as a result of hydrothermal processes [**S38**].

Table 5.6 Biogeochemical Flows at the Atmosphere and Oceans Interface[1]

	Description	Code	Stock	Flow	Units	Source/Comment
	Fluxes to Atmospheric Stocks					
1	Release of carbon dioxide	[C66]	C dioxide	90.0	Pg C yr^{-1}	Denman *et al*. (2007).
2	Release of carbon monoxide	[C57]	C monoxide	<0.1	Pg C yr^{-1}	Prather & Enhalt (2001).
3	Release of methane	[C57]	Methane	<0.1	Pg C yr^{-1}	Prather *et al*. (1995), Schlesinger (1997), Houweling *et al*. (2000) & Weubbles & Hayhoe (2002).
4	Sea salt phosphate emissions	[P51]	Ocean inorganic P	0.3	Tg P yr^{-1}	Ruttenberg (2005).
5	Release of DMS	[S33]	Dimethyl sulfide	24.0	Tg S yr^{-1}	Kettle & Andreae (2000).
6	Release of hydrogen sulfide from sediments	[S55]	Hydrogen sulfide	0.8	Tg S yr^{-1}	Watts (2000), Nightingale & Liss (2006).
7	Other release of hydrogen sulfide	[S57]	Hydrogen sulfide	1.4	Tg S yr^{-1}	Watts (2000), Nightingale & Liss (2006).
8	Release of carbonyl sulfide	[S57]	Carbonyl sulfide	0.2	Tg S yr^{-1}	Mopper & Zika (1987), Mukai & Ambe (1986), Watts (2000), Nightingale & Liss (2006).
9	Release of carbon disulfide	[S57]	C disulfide	0.2	Tg S yr^{-1}	Xie & Moore (1999), Watts (2000), Nightingale & Liss (2006).
10	Sea salt sulphate emissions	[S52]	Atmospheric sulphate	144.0	Tg S yr^{-1}	Schlesinger (1997).
	Fluxes from Atmospheric Stocks					
11	Ocean uptake of carbon dioxide	[C77]	C dioxide	92.8	Pg C yr^{-1}	Denman *et al*. (2007).
12	Atmospheric deposition of ammonia	[N3]	Ammonia/ ammonium	19.4	Tg N yr^{-1}	Gruber & Galloway (2008).
13	Atmospheric deposition of nitrate	[N4]	N oxides	20.6	Tg N yr^{-1}	Gruber & Galloway (2008).
14	Atmospheric deposition of aerosol P	[P5]	Phosphate aerosols	0.3	Tg P yr^{-1}	Duece *et al*. (1991) & Ruttenberg (2005).
15	Atmospheric deposition of aerosol P	[P5]	Phosphate aerosols	0.8	Tg P yr^{-1}	Duece *et al*. (1991) & Ruttenberg (2005).
16	Atmospheric deposition of sulphur dioxide	[S6]	S dioxide	14.0	Tg S yr^{-1}	Calculated as balance flux for the S dioxide stock; ensuring that S deposition to the oceans is around one-third of total deposition (Schlesinger, 1997).
17	Atmospheric deposition of sulphate	[S7]	Atmospheric sulphate	155.4	Tg S yr^{-1}	Calculated as balance flux for the S dioxide stock; ensuring that S deposition to the oceans is around one-third of total deposition (Schlesinger, 1997).

Note: 1. Excludes flows associated with denitrification [N22, N23, N24] and N-fixation [N50].

5.7.5 Lithosphere and Terrestrial Biosphere Interface

The weathering of minerals marks the transfer of elements out of a phase of very slow geochemical cycling in the lithosphere, into a phase of more rapid cycling within the terrestrial biosphere. Given that a significant proportion of the dissolved products of rock weathering are carried by rivers to the sea, many biogeochemical cycling models include weathering processes as direct flows from the lithosphere to the ocean. In the ESAM, however, weathering rates are specified as flows from the lithosphere to the terrestrial biosphere, separate from river transport flows.

The rate of N weathering [**N79**] is set as 5 Tg N. In terms of the C cycle, the dominant weathering process is a form of chemical weathering. CO_2 dissolves in the soil solution to form H_2CO_3, which reacts with the minerals on land. Much of the dissolved products from this reaction are then carried by surface runoff to the ocean. As this process decreases the release of CO_2 into the atmosphere from soil solutions, it essentially acts as a net sink for atmospheric CO_2. The loss of lithosphere C from rock carbonates as a result of weathering [**C79**] is around 0.2 Pg, with the process also resulting in an equivalent loss of atmospheric CO_2 (Prentice *et al*., 2001; Denman *et al*., 2007).

Weathering of continental bedrock is an important process within the P cycle, as it is the only major source of 'new' P to soils. The total weathering flow from the other lithosphere P stock to the soil inorganic P stock [**P79**] is set to 20 Tg P (Ruttenberg, 2005). Although P solubilized during chemical weathering is available for uptake by terrestrial plants, a large proportion is involved in reactions with other soil minerals, leading to its precipitation in unavailable forms (Brimblecombe, 2005). No attempt is made to separate the reactive and unreactive forms of inorganic P in the terrestrial reservoir. The ESAM also incorporates an S weathering flow [**S79**] of 74 Tg S, derived from the average of the values given by Schlesinger (1997) and Brimblecombe (2005).

Having considered the flow of elements out of the lithosphere to the terrestrial biosphere, it is now time to consider flows in the opposite direction. Many publications only record input flows to the lithosphere via ocean sediments. Nevertheless, the presence of large coal deposits, which has its origins in terrestrial organic matter, indicates the sedimentation and burial of terrestrial materials have at least occurred in the past. There is little information on the rate at which elements within terrestrial organic matter are become permanently buried.

The flows are, however, likely to be small when compared with other transfers. Assuming simply the same rate as coal formation, the net flow of organic C from the terrestrial biosphere to lithosphere is less than 1 x 10^{-5} Pg. Applying the stoichiometry of lignite, 177.9C:2.8N:1P:0.9S, to this C flow also produces very small estimates of organic N and S terrestrial burial flows, each less than 1 x 10^{-4} Tg [**71**].

In the case of P, flows from the terrestrial biosphere to the lithosphere are a little more significant, although still relatively small when compared with other components of the P cycle. Based on the work of Mackenzie *et al.* (1993), Lerman *et al*. (1975), and Jahnke (1992), Ruttenberg (2005) estimates the total exchange of P from soils to the lithosphere due to deep burial and lithification as 9.3–18.7 Tg P. The mid-point of this range is adopted, with the source assumed to be entirely from the soil inorganic P stock [**P40**].

5.7.6 Lithosphere and Atmosphere Interface

In addition to the loss of crustal materials via weathering, inputs of elements to the lithosphere from ocean sedimentation are balanced by outputs of elements through degassing of the Earth's interior. Quantification of the rate of degassing of CO_2 is one of the most pressing problems in modelling the global C cycle (Berner and Lasaga, 1989). This is largely due to difficulties in estimating the CO_2 flow from continental rifts, as well as accounting for extreme point source emissions from sporadic volcanic events (Fisher, 2008). Global estimates of CO_2 released from volcanoes are between 0.02 and 0.05 Pg C yr^{-1} (Williams *et al*., 1992; Bickle, 1994). The total lithosphere CO_2 emission adopted is 0.05 Pg C [**C35**], derived by taking an estimated total C flow of 0.06 Pg C (Mackenzie *et al*., 1993), and subtracting the estimated CH_4 flow [**C34**, **C65**] of 0.01 Pg C (Prather *et al*., 1995; Wuebbles and Hayhoe, 2002; Wang *et al*., 2004).

As with estimates of C emissions from the lithosphere, due to data paucity it is difficult to provide estimates of the total global transfer of S gases from the lithosphere. Based on the work of Stoiber *et al*. (1987), Berresheim and Jaeschke (1983), and Bates *et al*. (1992), Schlesinger (1997) estimates total volcanic emissions of S as 10 Tg. Brimblecombe (2005) provides a conservative estimate of 10.4 Tg S, of which around 65 percent is SO_2. These estimates are taken from Andres and Kasgnoc (1998) and do not include S flows associated with semiperiodic, but infrequent, large eruptions. Noting this limitation, the SO_2 volcanic

emission estimate of Andres and Kasgnoc (1998) is incorporated into the ESAM, along with their estimates of the H_2S, CS_2, and OCS flows [**S36**].

Chapter 6

Is there Overshoot of Planetary Limits? New sustainability indicators based on 'Ecotime' analysis

6.1 Introduction

Recognising that biogeochemical cycling underpins the provision of many important ecological services to humankind, and that these cycles, in turn, are bound to operate and function within certain physical constraints, brings to the forefront the issue of 'scale'. Scale has been defined as the "physical size of the economic subsystem relative to the ecosystem that contains and sustains it" (Daly and Farley, 2010, p.12). As already explained in Chapter 2, the issue of an appropriate scale for human activities has become a core focus for many persons concerned with sustainability. Research relating to this issue has sought to address questions such as: How can we assess the present scale of the economy at a global level? Can we express an opinion on the present direction of changes in that scale? Is it possible to establish which scale would be sustainable? (Røpke, 2005). The scale issue is also strongly related to the concept of resilience in that the greater the scale of the economy, the greater the risk of closing welfare opportunities for future generations, or even destroying the conditions for human life in the long run.

The particular focus of this chapter is on devising a method that enables us to evaluate the scale of human activities relative to the scale of biogeochemical cycles. The method rests on the calculation of a set of 'values' that enable different types of ecological commodities to be compared in commensurate terms, based on the differing times available for matter held within these commodities to reach key biogeochemical processes. In the same manner as a building due for maintenance in 10 years will be considered more valuable than a building due for maintenance in only one year, matter having recently passed through a biogeochemical process, such as photosynthesis, is consider to hold higher 'value' in relation to that process than matter accumulating in stocks before such processing. Throughout this chapter, this time-based measure of relative biogeochemical cycling value is referred to as 'ecotime'.

Once a set of ecotimes have been determined for each ecological commodity, it then becomes possible to produce a suite of indicators that describe the extent to which the global economic system, through its transformation of useful resources (i.e. raw materials) into residuals (i.e. wastes, pollutants, emissions), is consuming or 'appropriating' the Earth's biogeochemical cycles. The relative scale of the global economy can be ascertained by comparing the rate at which ecotime is consumed by the global economy, and the rate at which it is regenerated by the biosphere. Furthermore, the chapter demonstrates how the appropriation of biogeochemical cycles, as measured in ecotime, can be traced through economic production chains, and ultimately attributed to final consumer goods.

The chapter is structured as follows: Section 6.2 outlines the major antecedents to the indicators put forward in this chapter, briefly explaining where the approach is consistent with, deviates from, or extends these earlier attempts. Section 6.3 provides a set of definitions for key terms, while Section 6.4 provides a full mathematical specification of the ecotime method. Section 6.5 describes the datasets drawn on in applying the ecotime method. Results and discussion are presented in Section 6.6, followed by concluding comments in Section 6.7.

6.2 Major Antecedents of Ecotime Analysis

6.2.1 Ecological Footprint

The Ecological Footprint (EF) concept (Wackernagel and Rees, 1996, 1997), and other indicators such as the Human Appropriation of Net Primary Productivity (HANPP), have generated significant debate on how to conceptualise scale and the state of the environment (Røpke, 2005). In terms of the HANPP, for example, Vitousek *et al*. (1986) found that 40 percent of terrestrial NPP is "used directly, co-opted or forgone because of human activities". Similarly, but earlier, Catton (1982) developed the concept of 'ghost acreage', being the additional land a nation would need to obtain food, fuel and other products that it doesn't biologically produce within its own borders. Catton found, for example, that many western nations imported significant quantities of fossil fuels (i.e. historical biological production) to support their economic requirements.

The EF methodology uses 'biocapacity' to measure the capacity of the planet to provide useful raw materials and absorb residuals produced by humans. Operationally, biocapacity is measured as the sum of available bioproductive land areas. When an area's EF exceeds its

biocapacity, an 'ecological deficit' is said to occur. In this chapter, the term 'regenerative capacity' is preferred to 'biocapacity' when referring to the level of supply of ecological systems. The intention is to capture the idea that biogeochemical processes together constitute cyclical systems that continuously 'regenerate' over time. For example, carbon dioxide released during microbial decomposition is regenerated into new organic matter, inert N 'fixed' into reactive N via atmospheric lighting is regenerated as inert N during soil denitrification, methane released from landfills degrades to CO_2 and, following photosynthesis, is regenerated as economic crops, and so on. However, for a variety of reasons, this level or capacity of regeneration achieved by biogeochemical processes (i.e. the *rate* of regeneration) is subject to constraints.

Although the EF has widespread appeal due to its intuitive conversion of both demand and supply into a land metric (Zhang *et al*., 2010), a major criticism of the concept relates to the equivalence factors used to aggregate land of different types, as these do not adequately reflect differences in resource qualities and the extent to which different activities utilise or degrade natural capital. A recent modification is the EF based on NPP (Venetoulis and Talberth, 2008), which, using rates of NPP to calculate equivalence factors helps create a more robust method for the EF calculation. Nevertheless, by measuring humanity's demand on the planet simply according to the required area of ecologically productive land, many of the complexities of ecosystems and environmental impacts are still absent (McDonald and Patterson, 2004; McDonald *et al*., 2006). The method set out in this chapter addresses some of these concerns as the level of human impact can be determined with reference to a range of processes undertaken by biogeochemical cycles, including primary production, but also many others.

6.2.2 Emergy Analysis

Other commentators have noted that embodied energy or Emergy (Odum, 1983, 1988, 1996, 2000) may provide an avenue for extending the EF method (Wackernagel and Yount, 2000), given that it presents a means of quantifying the contribution of many different ecological processes to economic activities. Emergy, derived from the idea of 'energy memory', is usually defined as the available energy used up both directly and indirectly to generate resources (Odum, 1996). One should note, however, that the Emergy approach incorporates some quite distinctive assumptions or 'algebra rules' relating to the way in which all the necessary

ecological inputs necessary for production of a particular good or service are determined.[116] Emergy practitioners also adopt a specific approach to the calculation of the primary or 'baseline' energy flows (i.e. those flows used to set the relative values for all other commodities) that lead to the Unit Emergy Values assigned to crustal heat and tidal energy as being many thousand times higher than that which is applied to solar energy (refer to Odum (2000) and Brown and Ulgiati (2010)).

Rugani and Benetto (2012) recently suggested modifying the Emergy approach so that primary energy flows are individually quantified and assigned to different ecological commodities, depending on the necessary input of those energy flows to their production, e.g. sunlight required for water evaporation or the geothermal energy required for coalification. The amount of such primary energy required directly and indirectly to produce different ecological goods can then be calculated using matrix-based techniques from Life Cycle Assessment (Neri *et al*., 2014). Other authors have also suggested that the concept of Ecological Cumulative Exergy Consumption is closely related to Emergy, and even equivalent if "the analysis boundary, allocation method, and approach for combining global energy inputs" are identical (Hau and Bakshi, 2004, p.3768).

6.2.3 Ecotime Analysis

The method presented here for calculating the human appropriation of biogeochemical cycles has some similarities with the EF, Emergy, Ecological Cumulative Exergy Consumption, and even Life-Cycle Assessment approaches, but there are also significant differences. All of these methods, along with the one put forward in this chapter, apply, 'system based numeraires' (Patterson, 1998) to enable disparate objects or processes to be compared in equivalent terms based on interdependencies or linkages within a system. The other methods, however, are primarily concerned with looking at the production system 'upstream' of the particular commodity under consideration, and calculating scarce inputs (e.g. land, energy) required directly and indirectly to produce that commodity. This method concentrates instead on tracing the production chain 'downstream' of the commodity and calculates the length of time required to reach a particular biogeochemical process of interest.

[116] Refer to Sciubba and Ulgiati (2005) for a discussion on the distinction between co-products and splits within Emergy algebra.

The very cyclic nature of the Earth's biogeochemical cycles has led to the conception of a time-based approach for comparing ecological commodities, rather than an approach that attempts to calculate all of the biogeochemical inputs necessary for production of a commodity. To explain further, using an example, imagine a very simple and purely hypothetical C cycle (Figure 6.1) which involves just four types of C commodities: atmospheric CO_2 (a), plants (p), soil (s), and lithosphere C (l). The average residence times for C held within these stocks are given as 5 years, 15 years, 70 years, and 900 million years, respectively. Imagine also that each year, 50 Pg of C are cycled through this system, and that the primary energy input driving the system occurs by way of the incorporation each year of 2 zetta joules (ZJ) of exergy during photosynthesis. Taking an input-based approach, we can immediately see, as plant matter is created directly as an output of photosynthesis, that 2 ZJ of energy are required for the production of 50 Pg of plant matter. However, as soil is then produced by plant matter, 50 Pg of soil must also 'embody' the same level of energy inputs. As we follow the cycle round we eventually get back to the beginning, meaning that all inputs are dependent on each other, and there becomes no easy way to differentiate the relative 'values' of different types of ecological goods. By comparison, under a time-based approach it is relatively straightforward to differentiate between ecological commodities relative to the process of photosynthesis. The average C atom held within plants must cycle through the soil, lithosphere and CO_2 stocks prior to reaching the process of photosynthesis, and thus has a remaining cycling time of well over 900 million years. This differs markedly from an atom of C held within CO_2, which has less than five years.

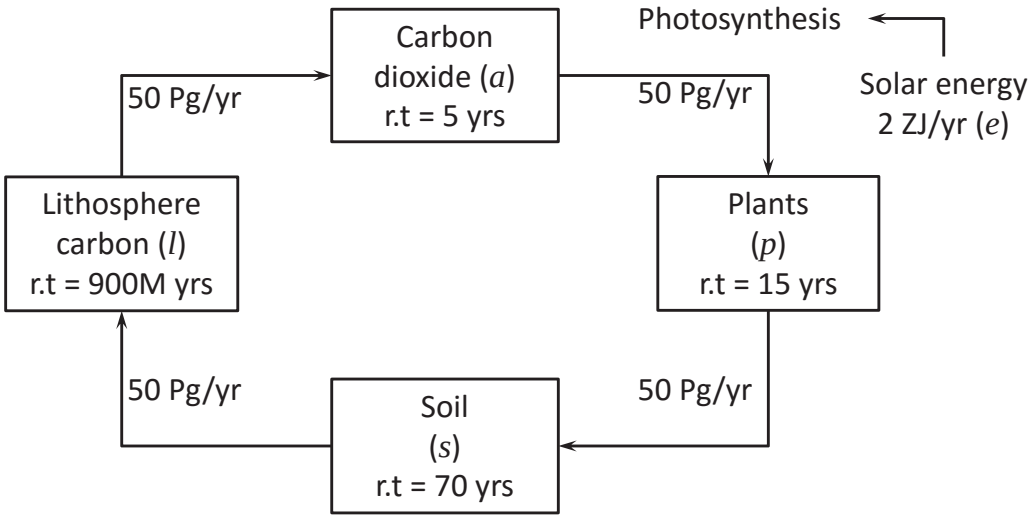

Figure 6.1 Hypothetical Carbon Cycle

Note: 'r.t' is the residence time of an ecological commodity

Note that scarce inputs to biogeochemical processes, such as solar energy in the above example or land as typically used in the EF, do not enter directly into any of the calculations put forward in this chapter. Nevertheless, because the method describes the level of demand for biogeochemical processes relative to their supply, and biogeochemical processes, in turn, require other inputs such as energy and land for operation, the method can potentially still provide important insights into the level of any gap in supply or overshoot of such scarce resources.

6.3 Definitions

Given that the method introduced in this chapter is novel, incorporating a number of new concepts, it is helpful to provide readers at the outset with a set of key terms and definitions (Table 6.1) that are then used throughout remainder of this chapter.

Note that ecotimes are calculated for each ecological commodity relative to a designated biogeochemical process (or set thereof), which then become the key units of measurement for the analysis. Essentially ecotime is a measure of the average cycling time available for matter held within differing types of ecological commodities needed to reach a particular biogeochemical process under consideration. The amount of ecotime that is effectively *demanded* each year by the global economy, because of the transformation of environmental resources into residuals is captured by the 'ecoconsumption' concept. The magnitude of ecoconsumption can then be compared with the level of regenerated cycling time *supplied* by global biogeochemical processes, termed 'regenerative capacity'. The degree of any 'ecological overshoot' is then calculated simply by dividing ecoconsumption by regenerative capacity. Note that the ecological overshoot concept is technically dimensionless, as the units of the numerator and denominator cancel each other out. However, to help readers interpret the results we can refer to the 'years' of a particular biogeochemical process appropriated when measuring ecological overshoot.[117] These values are, however, always with reference to one year of operation of the global economy, i.e. years per year, which is also dimensionless. A set of 'ecoprices' are also calculated that tell us, for every monetary unit worth of an economic commodity consumed, the total loss of ecotime necessary to produce that commodity.

[117] By analogy, the EF is sometimes recorded as the equivalent number of planets appropriated.

Table 6.1 Key Terms and their Definitions

Term	Symbol	Definition	Method/ formula for calculation	Unit
Ecotime	$\varepsilon_n^{e,m}$	The average length of time for matter of element e and held within an ecological commodity n to reach a designated biogeochemical process m.	Derived from (1) a supply-side input-output model that traces the cycling pathway forward for matter through various ecological commodity stocks, and (2) the average residence times for matter within each of these commodity stocks.	years
Ecoconsumption	$ecocon^{e,m}$	A weighted sum of all of the element e and process m ecotime consumed by the global economy as a result of its resource use and residual/waste generation.	$ecocon^{e,m} = \sum_n \left(\left(resource_n^e - waste_n^e \right) \times \varepsilon_n^{e,m} \right)$ where: $resource_n^e$ = annual consumption of ecological commodity n by the global economy (Pg of element e), and $waste_n^e$ = annual production of ecological commodity n by the global economy (Pg of element e).	Pg years
Regenerative capacity	$regcap^{e,m}$	A weighted sum of all of the element e and process m ecotime produced by the global environment as a result of biogeochemical processes.	$regcap^{e,m} = \sum_n \left(\left(esup_n^e - euse_n^e \right) \times \varepsilon_n^{e,m} \right)$ where: $esup_n^e$ = annual production of ecological commodity n by all ecological processes (Pg of element e), and $euse_n^e$ = annual consumption of ecological commodity n by all ecological processes (Pg of element e).	Pg years
Ecological Overshoot	$ovshoot^{e,m}$	The ratio of ecoconsumption to regenerative capacity for element e and designated process m.	$ovshoot^{e,m} = \frac{ecocon^{e,m}}{regcap^{e,m}}$	dimensionless
Ecoprice	$\upsilon_i^{e,k}$	The total loss of element e and process m ecotime necessary to produce an economic commodity i for consumption.	Derived from (1) a demand-side input-output model that traces all of the environmental resource use and waste production required directly and indirectly to produce each unit of an economic commodity, and (2) the net loss of ecotime associated with this resource use and waste creation.	Pg years/ monetary unit (e.g. Pg years/ US$)

6.4. Mathematical Specification

The method is a synthesis of two types of IO approaches. First, a supply-side IO model is used to develop comparable ecotimes for each ecological commodity. To derive these ecotimes, the model traces the cycling pathway forward for each ecological commodity, identifying all of the downstream (i.e. forward linkage) commodity stocks through which matter originating from a particular commodity must pass before reaching a biogeochemical process under consideration. Commodities within the biogeochemical cycling system, which have available the greatest amount of time before needing to pass through a particular process, receive the highest ecotimes relative to that process. Once the set of commodity-based ecotimes are calculated, these values can be combined with data on current rates of resource use, residual generation, and 'natural' biogeochemical processing in order to derive the ecoconsumption, regenerative capacity, and ecological overshoot indicators – as per the formulas specified in Table 6.1. The only additional aspects requiring explanation (i.e. apart from the method of calculating ecotimes that is given in Section 6.4.1. below) are the following identities, based on the framework given in Figure 3.4, and the terms directly referred to in Table 6.1:

$$resource_m^e = \sum_{j=1}^{\sigma} \tilde{r}_{m,j}^{\mathrm{p},e} + \tilde{r}_m^{\mathrm{o},e},$$

$$waste_m^e = \sum_{j=1}^{\sigma} \tilde{w}_{j,m}^{\mathrm{p},e} + \tilde{w}_m^{\mathrm{o},e},$$

$$esup^e = \sum_{n=1}^{\pi} \tilde{b}_{n,m}^e, \text{ and}$$

$$euse^e = \sum_{n=1}^{\pi} \tilde{a}_{m,n}^e.$$

Second, and so as to help understand the economic drivers behind the aggregate results calculated, a demand-side IO model is used trace the upstream (i.e. backward linkage) net consumption of ecotimes by the global economic system through economic production chains, ultimately attributing this consumption to final goods, using a consumer-responsibility

perspective.[118] The net consumption of ecotime, per unit of each commodity produced for final consumption, constitutes the commodity-based ecoprices.

6.4.1 Calculation of Ecotimes

Following the framework given in Figure 3.4, data on mass flows through the global environment is provided in a commodity-by-process format (i.e. matrices $\tilde{\mathbf{A}}$ and $\tilde{\mathbf{B}}$). If we were to take C flow data for, say, NPP, soil respiration and litter fall, and represent this information in a diagram, it would look something like Figure 6.2 below.[119] Essentially, we know the mass inputs and outputs required for each respective process (shown as hexagons), and for each process total mass inputs equal total mass outputs. Now, to calculate ecotimes for each commodity (shown as oblongs), our first task is to transform the commodity-by-process flow data into a set of equations describing mass flows directly between commodities. The data contained within Figure 6.2 can, for example, be represented in a commodity-by-commodity flows format as per Figure 6.3.

Conversion into a commodity-by-commodity representation is achieved by application of an ITA, as applied within IO analysis to transform economic SUTs into symmetric commodity-by-commodity matrices.[120] The sub-matrix $\tilde{\mathbf{Z}}^{\mathrm{C}}$, which denotes a commodity-by-commodity mass flow matrix for the element C, is determined by the equation,

$$\tilde{\mathbf{Z}}^{\mathrm{C}} = \left(\mathbf{i}\tilde{\mathbf{A}}^{\mathrm{C}}\right)^{-1} \tilde{\mathbf{A}}^{\mathrm{C}}\tilde{\mathbf{B}}^{\mathrm{C}},$$

[118] For an explanation of the alternative consumer and producer-responsibility perspectives, refer to Lenzen *et al*. (2007).
[119] To avoid complexity only three biogeochemical processes are portrayed. Note that in order to achieve mass balance for each environmental commodity stock, all processes would need to be included (both anthropogenic and non-anthropogenic), along with any net changes to stocks.
[120] Refer to Section B.2.1 of Appendix B.

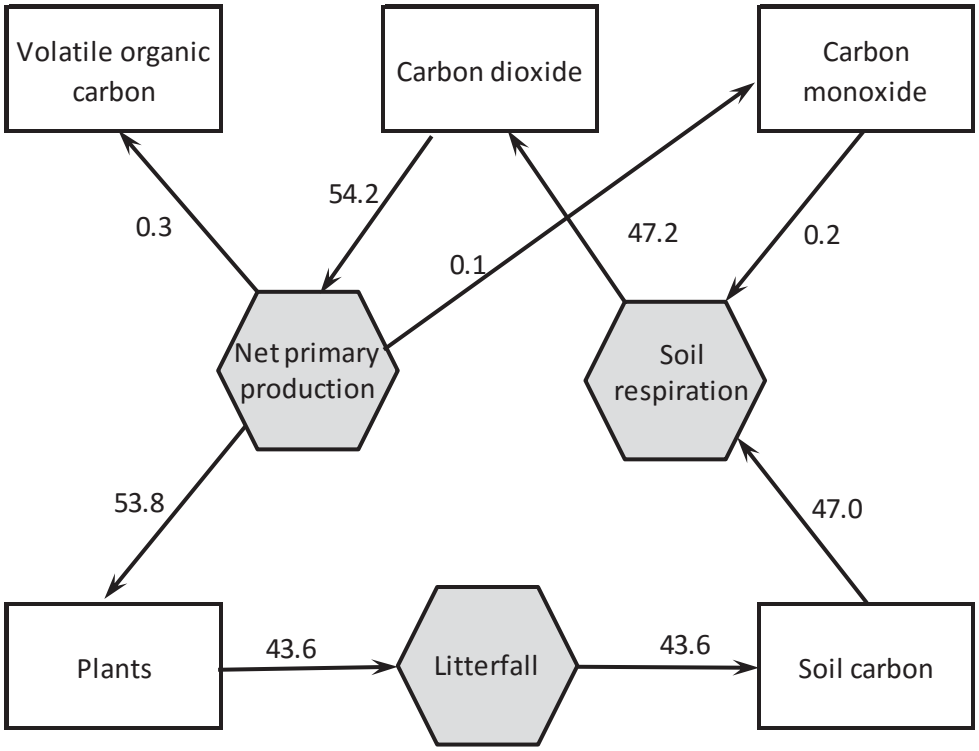

Figure 6.2 **Commodity-by-Process Representation of Biogeochemical Mass Flows (Pg C yr^{-1})**

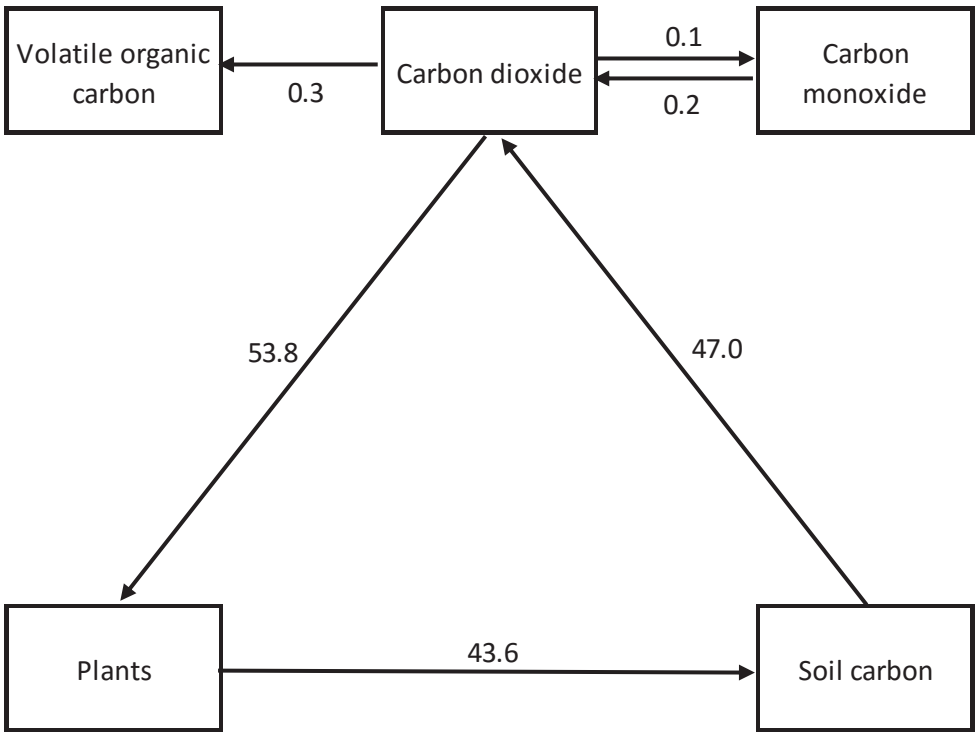

Figure 6.3 **Commodity-by-Commodity Representation of Biogeochemical Mass Flows (Pg C yr^{-1})**

where $\mathbf{i}$ is a row vector of ones, and the hat symbol (^) above the vector $\mathbf{i}\tilde{\mathbf{A}}^{C}$ is used to indicate vector diagonalisation. The remaining sub-matrices of $\tilde{\mathbf{Z}}$, pertaining to the other element cycles, are determined in an analogous manner.

It is noted that some of the early applications of IO analysis to trace matter/energy flows through ecosystems (e.g. Herendeen and Bullard (1974), Hannon (1979)) were subject to criticism on the basis that this approach presupposes a symmetric system where, not only is the number of processes equal to the number of commodities, but each process must also produce only one type of commodity. As these conditions are rarely satisfied it was thought likely that analysts would artificially aggregate commodities and/or processes to produce the required matrix (Fruci *et al*., 1983; Patterson, 2002). Such limitations do not apply to this method, as it does not require the direct specification of a symmetric system as a starting point. Instead, the starting point is a set of non-square supply and use matrices, which inherently allow for situations of joint production, e.g. both plant matter and volatile C emissions are produced during primary production. The ITA, which is then used to generate the commodity-by-commodity system, is an appropriate assumption for the application. It implies that when multiple commodities are produced by a single process, the inputs to that process are allocated to the outputs on a pro-rata basis according to the relative element content of each output.

The Earth's biogeochemical cycles are now specified as a system of flows between commodity stocks, in a similar manner to that represented in Figures 6.1 and 6.3 above. However, while these figures show relatively simple systems of biogeochemical processes, the 'real world' of biogeochemical cycling is significantly more complex. Following photosynthesis, for example, there are several pathways through which C matter may flow. Some C may be respired and degraded relatively quickly back into CO_2 ready to enter a subsequent round of cycling, while other C passes into long-lived stocks within the oceans and lithosphere. The tools of IO analysis, which focus on tracing commodity production chains, provide a means of devising a description of the 'average pathway' through which matter flows during these cycles. Specifically, reliance is made on the supply-side mathematics (i.e. assessment of forward linkages) to trace the flow of matter *forward* from any *i* commodity, until the point that it re-enters the particular process under consideration.

Table 6.2 Aggregate Commodity-by-Commodity Input-Output Matrix of the Global Carbon Cycle (Pg C yr^{-1})

	Atmosphere	Terrestrial	Lithosphere	Oceans
Atmosphere		54.1		92.8
Terrestrial	52.0		0.0	0.8
Lithosphere	0.1	0.2		0.0
Oceans	90.6		0.5	

For this to be possible it is necessary to transform the commodity-by-commodity table so that the inputs and outputs of the particular *m* process constitute, using IO terminology, a column vector of 'final demands'[121] and a row vector of 'primary inputs'.[122] The flows contained within these vectors must then be otherwise removed (i.e. subtracted) from the commodity-by-commodity table. The term $\tilde{\tilde{\mathbf{Z}}}^{m}$ is used to denote the new commodity-by-commodity table. To help illustrate these steps, Table 6.2 above provides a very simple and aggregated biogeochemical mass flow matrix for C. The matrix $\tilde{\mathbf{Z}}^{\mathrm{C}}$ for this example is given simply as

$$\tilde{\mathbf{Z}}^{\mathrm{C}} = \begin{pmatrix} 0.0 & 54.1 & 0.0 & 92.8 \\ 52.0 & 0.0 & 0.0 & 0.8 \\ 0.1 & 0.2 & 0.0 & 0.0 \\ 90.6 & 0.0 & 0.5 & 0.0 \end{pmatrix}.$$

If we wish to create a $\tilde{\tilde{\mathbf{Z}}}^{\mathrm{C},m}$ matrix where *m* is the process of terrestrial NPP, responsible for transferring 53.8 Pg of C each year between the atmosphere and terrestrial commodity stocks, we have

$$\tilde{\tilde{\mathbf{Z}}}^{\mathrm{C,TNPP}} = \begin{pmatrix} 0.0 & 54.1-53.8 & 0.0 & 92.8 & 53.8 \\ 52.0 & 0.0 & 0.0 & 0.8 & 0.0 \\ 0.1 & 0.2 & 0.0 & 0.0 & 0.0 \\ 90.6 & 0.0 & 0.5 & 0.0 & 0.0 \\ 0.0 & 53.8 & 0.0 & 0.0 & 0.0 \end{pmatrix} = \begin{pmatrix} 0.0 & 0.3 & 0.0 & 92.8 & 53.8 \\ 52.0 & 0.0 & 0.0 & 0.8 & 0.0 \\ 0.1 & 0.2 & 0.0 & 0.0 & 0.0 \\ 90.6 & 0.0 & 0.5 & 0.0 & 0.0 \\ 0.0 & 53.8 & 0.0 & 0.0 & 0.0 \end{pmatrix}.$$

[121] Final demands encompass goods and services produced to satisfy final consumption, i.e. they are not used in the production of further goods and services.

[122] Primary inputs are those inputs to production that cannot be attributed to the output of a producing sector.

Reading across a row of $\overline{\tilde{\mathbf{Z}}}^{e,m}$ matrix tells us the mass of an element e supplied by the particular row-commodity to all other commodities, as well as the process m under consideration. An element of $\overline{\tilde{\mathbf{Z}}}^{e,m}$ divided by its row total therefore gives the 'supply coefficient'. Using element C again as an example, $\mathbf{\Gamma}^{\mathrm{C},m}$ is used to denote a matrix formed by subtracting a matrix of these supply coefficients, from an identity matrix of equivalent dimensions. In matrix notation, $\mathbf{\Gamma}^{\mathrm{C},m}$ can be calculated directly from $\overline{\tilde{\mathbf{Z}}}^{\mathrm{C},m}$ as,

$$\mathbf{\Gamma}^{\mathrm{C},m} = \mathbf{I} - \left(\overline{\tilde{\mathbf{Z}}}^{\mathrm{C},m} \mathbf{i} \right)^{-1} \overline{\tilde{\mathbf{Z}}}^{\mathrm{C},m} .$$

If we now let $\ddot{\mathbf{\Gamma}}^{\mathrm{C},m}$ denote a matrix that is identical to $\mathbf{\Gamma}^{\mathrm{C},m}$, but excludes its last column and row, the inverse of $\ddot{\mathbf{\Gamma}}^{\mathrm{C},m}$ describes, for every mole of C in row commodity n, the moles of C in all n' column commodities that can then be produced, because of downstream C cycling processes. This matrix describes the 'average' cycling pathway forward for an element of C contained within each of the various C commodities. Note that the tracing of these C flows along any pathway ceases once we complete the loop and return to the particular process under consideration. With the process of terrestrial NPP, for example, plant matter has a relatively 'long' calculated pathway, with an average mole of the commodity needing to pass through a number of C stocks, often more than once, prior to being absorbed as CO_2 during photosynthesis.

It is, however, unsatisfactory to measure the pathways of the C cycle simply according to the number of stocks through which matter must flow, as the results are highly determined by the level of stock disaggregation. In addition, some stocks hold matter for very long periods, thus slowing the rates of cycling, while in other cases matter flows very quickly through stocks. To address these issues, each stock is multiplied by its average residence time when calculating the 'cycling lengths' which ultimately define the relative ecotimes assigned to each commodity. In summary, the set of ecotimes for C commodities relative to process m, $\boldsymbol{\varepsilon}^{\mathrm{C},m}$, is calculated as,

$$\varepsilon^{\mathrm{C},m} = \left(\left(\ddot{\mathbf{\Gamma}}^{\mathrm{C},m} \right)^{-1} - \boldsymbol{\kappa} \right) \boldsymbol{\tau}^{\mathrm{C}} , \qquad (6.1)$$

where $\boldsymbol{\tau}^{C}$ is a column vector of C commodity residence times. The matrix $\boldsymbol{\kappa}$, which has diagonal elements equal to 0.5 and zero otherwise, is also added to Eq. 6.1 so that the final cycling lengths determined for each commodity type are for an average mole of C within the commodity stock, i.e. not a mole that has resided in the stock for its entire residence time. The ecotimes derived are measured in terms of the average years of biogeochemical cycling remaining for each commodity, relative to a particular process.

6.4.2 Tracing the Appropriation of Ecotimes through the Economic System

Once a set of ecotimes have been determined for any particular process, it is a straightforward task to trace the appropriation of these by the global economic system and, in turn, attribute this appropriation to different types of consumer goods. In matrix notation,

$$\boldsymbol{\upsilon}^{e,m} = \mathbf{L}^{-1}\boldsymbol{\rho}^{e,m}, \tag{6.2}$$

where, as explained in Table 6.1, $\boldsymbol{\upsilon}^{e,m}$ is the vector of ecoprices for all *i* economic commodities relative to process *m* and element cycle *e*, and $\mathbf{L}$ is the Leontief matrix as commonly used within IO analysis. The vector $\boldsymbol{\rho}^{e,m}$ measures the process *m* ecoconsumption to produce a unit of each economic commodity. It is derived from information on resource use and residual generation for each production activity, along with the relative ecotimes of resources and residuals. Thus,

$$\boldsymbol{\rho}^{e,m} = \left(\left(\boldsymbol{\varepsilon}^{e,m}\right)^{\mathrm{T}} \ddot{\mathbf{R}}^{e}\right)^{\mathrm{T}} - \ddot{\mathbf{W}}^{e}\boldsymbol{\varepsilon}^{e,m}, \tag{6.3}$$

where the matrix $\ddot{\mathbf{R}}^{e}$ (μ x ψ) defines the use of ecological commodity *n* in the production of economic commodity *i* ($n \in \{1...\psi\}$, $i \in \{1...\psi\}$), measured in Pg of element *e* per monetary unit. Similarly, matrix $\ddot{\mathbf{W}}^{e}$ defines the quantities of each ecological commodity produced as residuals, per monetary unit of production of each economic commodity.

In using a Leontief matrix in Eq. 6.2, the method presupposes that the data on economic transactions are provided in a symmetric IO table; the initial framework, however, allows for non-square supply and use tables ($\mathbf{V}$ and $\mathbf{U}$) as a starting point. The commodity-by-commodity model set out in Appendix B (Section B.2.1) allows for the required symmetric tables to be

calculated based on various combinations of the ITA and CTA, without generation of negative elements. Note also that the matrices of resource use and residual generation in Eq. 6.3, i.e. $\ddot{\mathbf{R}}^e$ and $\ddot{\mathbf{W}}^e$, must be defined by economic commodity rather than by economic process; however, the collection of such data is often at an industry or process level, as per the framework given in Figure 3.4. Appendix B also explains how to transform these matrices into the required form, if one treats them as analogous to primary inputs in the commodity-by-commodity model.

6.5 Data Sources

In order to illustrate the above method, this chapter draws directly on the extensive ESAM database developed primarily within Chapters 4 and 5, namely the within-environment flows ($\tilde{\mathbf{A}}$ and $\tilde{\mathbf{B}}$), and flows between the environment and economy ($\tilde{\mathbf{R}}^{\mathrm{P}}, \tilde{\mathbf{R}}^{\mathrm{h}}, \tilde{\mathbf{W}}^{\mathrm{p}}$ and $\tilde{\mathbf{W}}^{\mathrm{h}}$). Additionally, the data on within-economy flows required by Section 6.4.2 ($\mathbf{V}$ and $\mathbf{U}$) are taken directly from the GTAP 7.0 database. The residence times for an ecological commodity n, τ_n^e, are calculated simply by dividing the total stock of an ecological commodity by the annual ecological flow out of the stock. Thus,

$$\tau_n^e = \frac{\delta_n^e}{\sum_{n'=1}^{\mu} \tilde{Z}_{n,n'}},$$

where δ_n^e is the estimated total stock of element e within commodity n. Adopted environmental commodity stock values are set out in Table E.1-E.4 of Appendix E, while Table E.5 provides a concordance mapping the use of these stock values between chapters.

6.6 Results and Discussion

6.6.1 Summary Results

Table 6.3 highlights the way in which the global economic system appropriates biogeochemical cycling processes for each of the C, N, P and S cycles, through its taking up of various resources, and subsequently transforming them into residuals. The results show that although humans are putting significant pressure on the biogeochemical cycles, the impacts on the

global C cycle are by far the most significant. Essentially, the world's economic system is extracting huge quantities of C presently held in long-resident lithosphere stocks (e.g. fossil fuels, carbonate minerals), and transforming these into waste products (mainly CO_2). The magnitude of ecoconsumption associated with these matter transformations is equivalent to over 20 years of the current regenerative capacity, for most of the different C cycling processes considered.

As explained above, the method for developing these indicators depends on the calculation of an 'average pathway forward' for matter in a biogeochemical cycle, starting from a given commodity stock. For the C cycle, for example, a general pattern exists in that a high proportion of C matter repeatedly passes through the fast organic cycles of production and respiration, and a very small portion of C flows through slow lithosphere cycles. Overall, it is estimated that every mole of C moved out of the lithosphere by humans and into the atmosphere/terrestrial environment pushes that matter forward by some 470 million years through average biogeochemical cycle processing, meaning a total ecoconsumption of 3,900 million Pg C years, when 8.2 Pg of lithosphere C are consumed.

These impacts, depicted in Table 6.3, are measured relative to regenerative capacity for a selection of biogeochemical processes, thereby providing an ecological overshoot indicator for each process. Importantly, 'natural' biogeochemical processes are currently responsible for removing C from the atmosphere at a faster rate than natural emissions. Although this net use of atmospheric C is partly balanced by an increase in vegetation and other terrestrial C commodities (generally similar ecotimes to atmospheric commodities for many processes), there are also some current increases in oceanic C stocks, as well as likely small increases in sediment/kerogen C. For processes operating within the atmosphere, terrestrial biosphere, and oceans, such matter transfers are 'opposite' to those caused by human activities; creating a net increase in C ecotimes. Nevertheless, the level of regenerative capacity currently displayed by the global C cycle is significantly less than ecoconsumption, leading to relatively significant overshoot indicators for all of the processes considered in Table 6.3. The reason that the overshoot indicators are similar among the terrestrial and oceanic processes within the C cycle (overshoot ≈ 23) is that, for each of these processes, the calculation of regenerative capacity is dominated by the rate at which natural processes lead to an accumulation of long-residence lithosphere/sediment C, at the expense of atmospheric C. For each of these terrestrial and oceanic processes, a net exchange of one mole of atmospheric C for one mole

of lithosphere C effectively means the matter 'moves back' in cycling time by a similar number of years.

It is interesting to note that the level of overshoot calculated for each of the atmospheric C processes within Table 6.3 (oxidation of CH_4 to CO, oxidation of CO to CO_2, oxidation of VOC to CO_2) is somewhat lower than that of the terrestrial and oceanic processes. This occurs because each of the processes involves the transformation of a less-stable, reduced atmospheric gas to a more stable, oxidised species. Due to the relatively unconstrained nature of these processes within the atmosphere, the processes have drastically increased in rate in response to growing anthropogenic emissions of C gases and now current rates of oxidation are significantly higher than the 'natural' rates at which these gases are produced. Hence, the atmospheric processes are more effective at 'speeding up' in response to anthropogenic perturbation compared to the terrestrial and oceanic processes considered.

In the case of the N cycle, the human impacts over a single year are also estimated to be equivalent to more than one year of cycling, for the majority of processes considered. Among the most significant human impacts on the global N cycle is the transformation of otherwise inert N_2, into reactive N, by way of N fixation. Presently, around 130 Tg of N yr^{-1} are fixed via the Haber-Bosch process (Canfield *et al*., 2010), around 60 Tg of N undergo biological fixation in agricultural systems (Herridge *et al*., 2008), and it is estimated that a further 10 Tg of N are fixed within internal combustion engines. Although the global N cycle is relatively effective in converting this N (and also N contained within fossil fuels) back into long-resident stocks via denitrification, the calculated regenerative capacity is still lower than ecoconsumption, relative to all of the processes considered in Table 6.3.

Table 6.3 Ecological Overshoot Calculated for a Selection of Biogeochemical Processes, 2004

Biogoechemical Process	Cycle			
	C	N	P	S
Terrestrial net primary production (excl crops)	22.75	1.40	0.91	0.34
Terrestrial litter processing	23.19	1.35	1.04	0.49
Terrestrial N_2 fixation (excl crops)		1.41		
Denitrification in soils		1.40		
Release of NOx from soils		1.40		
Oxidation of CH_4 to CO	8.37			
Oxidation of CO to CO_2	6.00			
Oxidation of VOC to CO_2	10.24			
N_2 fixation by lightning		1.41		
Oxidation of SO_2				1.02
Atmospheric destruction of DMS				1.04
Stratospheric destruction of N_2O		1.71		
Atmospheric deposition of NO_3^-		1.14		
Atmospheric deposition of NH_3/NH_4^+		1.02		
Atmospheric deposition of PO_4^{3-}			0.91	
Atmospheric deposition of SO_4^{2-}				1.04
River export	23.29	1.40	0.91	0.34
Uptake of CO_2 by the oceans	22.75			
Release of CO_2 from the oceans	23.83			
Ocean $CaCO_3$ production	23.83			
Ocean net primary production	23.83	1.21	0.92	1.10
Ocean denitrification		1.21		
Other ocean detrital processing	23.83	1.21	0.92	1.09
Deposition of organic matter in ocean sediments	23.83	1.21	0.92	1.09
Sedimentation of $CaCO_3$ in coastal sediments	23.68			

In the case of the case of the P cycle, the results presented in Table 6.3 appear to show that human appropriation is less of a problem. Note, however, that the current estimates of P use are significantly higher than estimates of P residuals, implying relatively high rates of increase in anthropogenic P. As discussed further below, such increases in anthropogenic stocks are a source of uncertainty in the results – refer to Section 6.6.4 for further discussion.

Interestingly, results for the S cycle are quite varied. On the one hand, large quantities of S emitted into the atmosphere by human processes are leading to an overshoot of atmospheric S processes, including oxidation of SO_2, destruction of DMS and deposition of sulphate (SO_4^{2-}).

On the other hand, however, current rates of river and atmospheric transport of S to the oceans are quite high, effectively flushing S quickly away from the terrestrial biosphere where it would otherwise be subject to such processes as terrestrial NPP and litter processing and thus the overshoot indicators for these processes are only 0.34 and 0.49, respectively.

Over the long term, it may be argued that ecological overshoot values consistently greater than one, particularly for processes such as photosynthesis that cannot easily increase in rate due to limiting factors, are likely to indicate an unsustainable level of human impact on a biogeochemical cycle. One should, however, be careful to conclude that values below one indicate the opposite. The Earth's biogeochemical cycles are complex systems and oscillation in processing rates and commodity stocks is typical. Indeed, a process of self-regulation for current or past disturbances of these systems may require a state of higher regenerative capacity than ecoconsumption for some period.

6.6.2 Detailed Results for Terrestrial NPP

This section provides detailed results for the terrestrial NPP biogeochemical process. The purpose is twofold: to provide readers with a specific example of the information and calculations underpinning the generation of the summary indicators presented above, and to illustrate the use of the method contained within Section 6.4.2 for generating indicators specific to different types of consumer goods.

Regenerative Capacity relative to Terrestrial NPP

As already discussed, the most significant changes in C commodities currently occurring because of biogeochemical processes are net losses of atmospheric C, balanced by net gains in terrestrial C, ocean C, and sediment/kerogen C. Although the transfer of C from the atmosphere to terrestrial and ocean C commodities certainly brings about a net gain in ecotimes relative to terrestrial NPP, the magnitude of regenerative capacity for this process is most strongly determined by the net transfer of C into sediments. This is because once C is buried within sediments, it becomes held up in very slow lithosphere processes, and many millions of years must pass before that C will again be subject to terrestrial NPP. Overall, the current matter transformations occurring within the biosphere produce a regenerative capacity relative to terrestrial NPP calculated as 170 million C years. In terms of the other elements, the regenerative capacity relative to terrestrial NPP is also assessed as some 930 million Pg N years, 1.61 billion Pg P years, and 160 million Pg S years.

Ecological Overshoot of Terrestrial NPP

Tables 6.4–6.7 below illustrate the calculation of human overshoot of terrestrial NPP, for the C, N, P and S element cycles. Column 2 of each table records the total quantity of each ecological commodity used by the global economy (in Pg) during 2004, which is then adjusted in Column 3 for use in the calculations (as explained below). Column 4 then records the quantities (in Pg) of residuals produced by the global economy over the same period. This then allows for net resource use for each commodity to be determined (Column 5).

The assessment of these impacts begins by calculating relative ecotimes for each type of ecological commodity, with these defined as the years of cycling available prior to terrestrial NPP occurring (Column 6). The total level of ecoconsumption in relation to each type of resource use/residual generation is then determined by a simple multiplication (Column 7). So that these impacts can be understood in context, it is helpful to measure them relative to the current regenerative capacity of terrestrial NPP, the extent of which has already been determined above. Thus, the final indicators produced (Column 8) are the calculated ecological overshoot.

Table 6.4 Calculation of Ecological Overshoot of Terrestrial Net Primary Production – Carbon Cycle, 2004

(1) Ecological Commodity	(2) Resource Use (Pg C)	(3) Adjusted[1] Resource Use (Pg C)	(4) Residual Generation (Pg C)	(5) Net Resource Use (Pg C)	(6) Ecotime (mil years)	(7) Ecoconsumption (mil Pg C years)	(8) Ecological Overshoot
Carbon dioxide	5.04	4.74	12.16	-7.43	4.6	-34	-0.20
Methane			0.28	-0.28	4.6	-1	-0.01
Carbon monoxide			0.58	-0.58	4.6	-3	-0.02
Volatile organic carbons			0.28	-0.28	4.6	-1	-0.01
Vegetation	5.12	4.81	0.62	4.19	5.1	21	0.13
Litter/detritus			4.06	-4.06	5.0	-20	-0.12
Other Soil Carbon	0.26	0.25	0.01	0.24	5.0	1	0.01
Coal	3.16	2.97		2.97	514.3	1,528	8.97
Petroleum	3.10	2.91		2.91	484.4	1,410	8.28
Natural gas	2.15	2.02		2.02	450.1	908	5.33
Carbonate minerals	0.31	0.29		0.29	220.3	65	0.38
Marine consumers	0.01	0.01		0.01	11.8	0	0.00
Total	19.15	17.99	17.99	0.00		3,873	22.75

Note: 1. Values are scaled down so that total resource use matches total residual generation.

Table 6.5 Calculation of Ecological Overshoot of Terrestrial Net Primary Production – Nitrogen Cycle, 2004

(1) Ecological Commodity	(2) Resource Use	(3) Adjusted[1] Resource Use	(4) Residual Generation	(5) Net Resource Use	(6) Ecotime	(7) Ecoconsumption	(8) Ecological Overshoot
	Pg N	Pg N	Pg N	Pg N	mil years	mil Pg N year	
Dinitrogen	0.187	0.178	0.018	0.160	6,787	1,088	1.17
Nitrogen Oxides			0.033	-0.033	6,699	-221	-0.24
Nitrous oxide			0.002	-0.002	6,776	-14	-0.02
Ammonia/ Ammonium			0.062	-0.062	4,618	-287	-0.31
Vegetation	0.057	0.055	0.015	0.040	2,435	96	0.10
Litter/detritus			0.133	-0.133	2,409	-321	-0.35
Other soil nitrogen	0.047	0.045	0.080	-0.035	2,409	-84	-0.09
Coal	0.054	0.052		0.052	11,502	597	0.64
Petroleum	0.012	0.012		0.012	36,265	426	0.46
Marine consumers	0.002	0.002		0.002	9,689	18	0.02
Total	0.360	0.344	0.344	0.000		1,299	1.40

Note: 1. Values are scaled down so that total resource use matches total residual generation.

Table 6.6 Calculation of Ecological Overshoot of Terrestrial Net Primary Production – Phosphorus Cycle, 2004

(1) Ecological Commodity	(2) Resource Use	(3) Adjusted[1] Resource Use	(4) Residual Generation	(5) Net Resource Use	(6) Ecotime	(7) Ecoconsumption	(8) Ecological Overshoot
	Pg P	Pg P	Pg P	Pg P	mil years	mil Pg P years	
Vegetation	0.017	0.011	0.001	0.009	27,068	256	0.16
Litter/detritus			0.021	-0.021	27,068	-557	-0.35
Other soil P	0.001	0.001	0.010	-0.010	27,068	-260	-0.16
Coal	0.013	0.008		0.008	54,965	439	0.27
Other crustal P	0.020	0.013		0.013	124,846	1,567	0.97
Marine consumers	0.000	0.000		0.000	125,382	21	0.01
Total	0.051	0.032	0.032	0.000		1,467	0.91

Note: 1. Values are scaled down so that total resource use matches total residual generation.

Table 6.7 Calculation of Ecological Overshoot of Terrestrial Net Primary Production – Sulphur Cycle, 2004

(1) Ecological Commodity	(2) Resource Use	(3) Adjusted[1] Resource Use	(4) Residual Generation	(5) Net Resource Use	(6) Ecotime	(7) Ecoconsumption	(8) Ecological Overshoot
	Pg S	Pg S	Pg S	Pg S	mil years	mil Pg S years	
Sulfur dioxide			0.063	-0.063	1,467	-92	-0.56
Carbon disulfide			0.000	0.000	1,266	0	0.00
Carbonyl sulfide	0.000	0.000	0.000	0.000	930	0	0.00
Hydrogen disulfide			0.004	-0.004	1,467	-5	-0.03
Dimethyl sulfide (DMS)			0.000	0.000	1,465	0	0.00
Vegetation	0.054	0.037	0.004	0.033	641	21	0.13
Litter/detritus			0.084	-0.084	641	-54	-0.33
Other soil S	0.028	0.020	0.017	0.003	641	2	0.01
Coal	0.064	0.044		0.044	1,196	53	0.32
Petroleum	0.064	0.044		0.044	1,581	70	0.43
Other crustal S	0.038	0.026		0.026	2,363	61	0.37
Marine consumers	0.000	0.000		0.000	1,909	0	0.00
Total	0.248	0.171	0.171	0.000		56	0.34

Note: 1. Values are scaled down so that total resource use matches total residual generation.

Table 6.4 illustrates how significant the current rates of C extraction from the lithosphere are, estimated at 8.7 Pg C in 2004, or 45 percent of all human C use during that year. The transformation of these commodities into waste products represents a huge loss in ecotimes currently held by global C, relative to the capacity of terrestrial NPP to regenerate ecotimes. It is calculated, for example, that every mole of coal combusted to atmospheric CO_2 moves that matter forward some 510 million years in the biogeochemical cycle closer to the process of terrestrial NPP (i.e. the equivalent of around 1,600 moles of C pushed through terrestrial NPP, or 290 moles of atmospheric C taken up by the oceans would be needed to produce the same gain in ecotime relative to terrestrial NPP). Humans are also responsible for extracting huge quantities of bio matter (nearly 5 Pg C in 2004), much of which ends up as organic residuals (litter/detritus), as well as CO_2. However, because the ecotimes for these substances do not vary significantly (Column 6), the contribution to the total impact (i.e. in Columns 7 and 8) is relatively low.

In the case of the P and S cycles, extraction of fuels and minerals from the lithosphere also represents a large proportion of total human resource use. However, unlike the C cycle, much of the residuals produced by the consumption of these resources are cycled through the biosphere and into the lithosphere without passing through the terrestrial NPP process. For example, a high proportion of SO_2 emissions are oxidised to SO_4^{2-} and then deposited, either in particulate or solution form, onto the oceans. Similarly, a high proportion of extracted P is transported relatively quickly, either through aerosols or within rivers, into coastal sediments. This means that unlike the case with the C cycle, the consumption of fossil fuels is not leading to a significant increase in P and S within stocks immediately upstream of terrestrial NPP.

6.6.3 Relative Indicators for Consumer Goods and Services

The economy's utilisation of the biogeochemical cycles through economic processes is traced in this section and allocated to final consumer goods and services. Table 6.8 first reports the total global consumption of different types of goods during 2004, as valued in US billions of dollars. A set of ecoprices, as measured in the loss of ecotime (relative to terrestrial NPP) embodied in each good, are then presented. The calculation of these ecoprices is based on all the direct and indirect resources and residuals necessary to produce those goods. When we multiply the ecoprice of a good, by the total value of that good consumed during a year, and then subsequently divide by the annual regenerative capacity of the biosphere, we arrive at the level of overshoot that can be attributed to the consumption of that good. Note that the

total overshoot calculated for each cycle is slightly less than totals reported in Tables 6.4–6.7 because this section focuses on only final consumer goods and services ($\mathbf{y}^{o}$ and $\mathbf{y}^{g}$). Table 6.8 therefore does not include calculation of overshoot embodied in goods produced for capital formation ($\mathbf{y}^{c}$), or associated with resources used and residuals created directly by households ($\tilde{\mathbf{r}}^{o}$, $\tilde{\mathbf{w}}^{o}$). These indicators are originally produced for 57 different types of commodities, but are aggregated to 23 commodity types for the purposes of reporting.

Interestingly, even goods/services produced with very little direct use of resources or production of residuals are relatively significant appropriators of biogeochemical cycling. For example, under the C cycle, the annual production of financial, insurance and business services involves a direct ecoconsumption of only around 100 Pg C years. However, taking into consideration all the direct and indirect inputs necessary for the production of these services, this ecoconsumption increases to over 100 million Pg C years (overshoot of 0.59).

The ecoprices can be utilised to illustrate particular inefficiencies within the economic system. The ecoprices show, for example, the very high level of impact associated with consuming fossil fuel commodities relative to the monetary cost of these commodities. Although this is unlikely to come as a surprise to most readers, the ecoprices certainly emphasise this situation. Additionally, the ecoprices can be utilised to ascertain the likely direction and magnitude of changes in pressure on biogeochemical cycling resulting from alternative patterns of consumption. To take a very crude example, a 20 percent increase in fuel efficiency by household vehicles (with no corresponding increase in travel) indicates a reduction in overshoot by around 3 percent.[123]

[123] This type of analysis assumes that the structure of the underlying economic and environmental systems remain constant. By analogy, many applications of economic IO analysis assume a constant economic structure (technical coefficients). As both the environment and economy are dynamic systems, subject to ongoing changes in structure, applications of this type, like those undertaken within IO analysis, are best suited to analysing relatively minor changes over short time frames.

Table 6.8 Terrestrial Net Primary Production Ecoprices for Consumer Goods and Services, 2004

Commodity	Global Household Consumption (US billion $)	Ecoprice (Pg C years/US billion $)				Total overshoot embodied in annual consumption			
		C Cycle	N Cycle	P Cycle	S Cycle	C Cycle	N Cycle	P Cycle	S Cycle
1 Rice and other grains	80	148.9	-206.8	-716.7	-0.9	0.07	-0.02	-0.04	0.00
2 Vegetables, fruits	370	90.7	46.7	-77.7	-4.2	0.19	0.02	-0.02	-0.01
3 Plant-based fibers	20	146.0	-140.8	-211.0	-4.8	0.02	0.00	0.00	0.00
4 Other crops	120	105.6	335.3	-42.4	1.0	0.07	0.04	0.00	0.00
5 Cattle, sheep & other animal products	150	89.8	7.2	-54.0	-17.6	0.08	0.00	-0.01	-0.02
6 Raw milk	50	96.5	-139.1	-60.3	-3.9	0.03	-0.01	0.00	0.00
7 Forestry	30	89.6	110.1	88.8	9.1	0.02	0.00	0.00	0.00
8 Fishing	80	151.4	163.5	156.2	6.3	0.07	0.01	0.01	0.00
9 Fossil fuels	20	4,896.3	773.1	580.0	86.4	0.53	0.02	0.01	0.01
10 Other minerals	10	379.9	52.8	3,116.2	108.6	0.01	0.00	0.01	0.00
11 Meat	330	93.3	-67.6	10.8	-2.0	0.18	-0.02	0.00	0.00
12 Other food products	2,020	96.3	25.0	-21.8	-1.2	1.14	0.05	-0.03	-0.01
13 Textiles and leather	990	97.6	49.0	15.2	0.1	0.57	0.05	0.01	0.00
14 Wood and paper products	400	116.2	40.6	26.1	-2.5	0.27	0.02	0.01	-0.01
15 Petroleum	310	1,701.3	446.4	95.8	54.1	3.07	0.15	0.02	0.10
16 Chemicals, rubber & minerals	830	243.3	328.4	79.5	2.6	1.18	0.29	0.04	0.01
17 Metals and metal products	100	162.0	50.4	148.5	0.0	0.09	0.01	0.01	0.00
18 Other manufactured products	1,980	97.7	47.6	53.5	0.4	1.14	0.10	0.07	0.01
19 Utilities & construction	610	809.6	193.0	181.8	-1.1	2.90	0.13	0.07	0.00
20 Trade	3,830	55.3	19.1	13.0	0.4	1.24	0.08	0.03	0.01
21 Transport & communications	1,490	185.9	45.6	20.9	3.9	1.63	0.07	0.02	0.04
22 Financial, insurance & business services	3,140	34.3	12.9	10.0	0.2	0.63	0.04	0.02	0.00
23 Other services	13,560	40.9	15.6	9.2	0.3	3.26	0.23	0.08	0.02
Total Commodities	30,500	102.7	38.4	15.9	0.8	18.40	1.26	0.30	0.15

6.6.4 Accounting for Economic Stock Changes

For each of the cycles considered, the difference between the quantity of matter extracted as resources from the environment and the quantity of matter released as residuals is quite significant (i.e. 1.2 Pg C, 16 Tg N, 18 Tg P, and 77 Tg S). To some extent, these stock changes are likely to be overestimated due limited reporting of organic waste composting. However, a proportion of these stock changes are also accounted for in residuals accumulating at landfill sites (estimated as 0.3 Pg C yr^{-1}, 13 Tg N yr^{-1}, 14 Tg P yr^{-1} and 41 Tg S yr^{-1}), as well as accumulation of 'capital' stocks within the economy (e.g. new buildings and infrastructure, growth in human and domestic animal biomass). Eventually, all matter entering the economic system, including that destined for landfills or capital stocks, is likely to be released back into the environment; however, at this stage no attempt is made to approximate the residence times of elements within the economy. Thus, in order to calculate the indicators presented in this chapter, the quantities of matter accumulating within the economy are not included. Instead, resource use in each of Tables 6.4–6.7 is adjusted so that it is equivalent to residual creation. Note also that since the method and data do not evaluate the particular resources necessary to produce these stock changes, it is assumed simply that economic stock changes originate from all resource inputs to the economy, according to the relative quantity of each resource extracted. The inclusion of economic stock changes is highlighted as a potential extension to the method requiring further work.

6.6.5 Sustainability and Ecotime Analysis

Terrestrial and oceanic processes would need to operate around 20 times faster than their current rates in order to balance-out human impacts on the C cycle, while for the N cycle the required rate of increase is around 20–40 percent. Appropriating biogeochemical cycling processes at a faster rate than these processes naturally occur, leads to an accumulation of elements within certain environmental stocks at the expense of others. Obvious examples include the accumulation of atmospheric and oceanic C, at the expense of lithosphere C, and the accumulation of reactive N at the expense of inert atmospheric N and lithosphere N. In terms of human welfare, the consequences of changes in the distribution of elements within biogeochemical stocks can be both positive and negative. The increased availability of reactive N to the terrestrial biosphere, for example, has helped to support food production for a rapidly growing human population (Galloway and Cowling, 2002). However, excess reactive N causes eutrophication of waterways, and acidification of soils, which threatens biodiversity.

Moreover, a build-up of nitrate in drinking water can harm human health, including increasing the risk of bowel cancer, while nitrous oxide is a major cause of stratospheric ozone depletion (Sutton *et al*., 2011; van Grinsven *et al*., 2013).

The ecotime indicators presented in this chapter are not intended, at this stage of development, to assist in the quantification of such impacts, but rather to shed light on the *present scale* of human perturbation of the biogeochemical cycles. Identifying changes in ecological processes and functions that may arise in response to altered stocks of biogeochemical species, and how these translate into ecosystem services, is highly complex – a topic for significant existing and likely future research. Research tools are required that consider not only connectivity between biogeochemical processes, but also relationships and feedbacks with other ecological functions. These tools must also be dynamic, as stocks build up or deplete through time, and many of the impacts are likely to occur in the future. It is further important to recognise that ecological systems are characterised by uncertainty and surprise as they behave in non-linear ways, display time-lagged responses, and may exhibit marked thresholds (Holling, 1992; Scheffer *et al*., 2001). Thus, we cannot ever fully predict the future consequences associated with current human perturbation of the biogeochemical cycles.

In the past the Earth has undergone significant biogeochemical changes, driven by both endogenous (e.g. biotic processes), and exogenous (e.g. meteorites) factors (refer to, for example, Sundquist and Visser, 2005). As explained in Chapter 2, the conventional view that the environment consists of systems that need to be maintained at, or near, an equilibrium has been overshadowed by an emerging view that systems exist within multiple stability domains or basins of attractions (Holling, 1973; DeAngelis and Waterhouse, 1987; Folke 2006). While sustainability does not necessarily imply maintaining a constant state in ecological systems, a focus on minimising human-induced changes in the system is important from a risk perspective. This helps avoid a possible transition to a new state that may be less beneficial to humans and potentially irreversible (Ayres, 1993; Arrow *et al*., 1995; Steffen *et al*., 2007; Rockström *et al*., 2009).

6.7 Summary

In a world characterised by uncertainty, where coupled environment-economic systems dependent on biogeochemical cycling have the potential to transition to stability domains not only less desirable, but potentially catastrophic to human existence, the creation of indicators that assess humanity's influence on these cycles is a crucial research agenda. This chapter presents a novel approach in these regards. Specifically, it describes a comprehensive and robust method for measuring humanity's overshoot of biogeochemical cycling systems. At present there are relatively few methods for communicating humanity's dependence on these cycles, yet impacts have the potential to go beyond the local or regional scale to affect the structure and functioning of the Earth system as a whole. On application of the method it has been shown that the Earth's economic system is responsible for absorbing significant quantities of 'ecotime' provided by the biogeochemical cycles, particularly with regards to the C cycle, but also to a lesser extent the N cycle. For the terrestrial and oceanic biogeochemical processes considered, more than 20 years of the current rate of regeneration provided by the C cycle is appropriated by the global economy within just one year.

Like other concepts such as the Ecological Footprint, HANPP, Emergy Analysis and Ecological Cumulative Exergy Consumption, ecotime analysis has the potential not only to deepen debate on the appropriate scale issue, but to do this explicitly with reference to the biogeochemical cycles. Ultimately, the determination of a safe and appropriate scale for human activities involves normative judgements of how societies choose to deal with risk and uncertainty. Where possible, indicators should be monitored over time, rather than presented as static numbers. If humanity overshoots the regenerative capacity of the biogeochemical cycles over a short period this may be of limited consequence as these cycles undoubtedly contain many self-regulating mechanism that enable recovery from perturbation. If, however, overshoot is persistent or increasing then the associated consequences may be irreversible and potentially catastrophic to human existence.

Part III: Dynamic Analysis

"the human mind is not adapted to interpreting how social systems behave. Our social systems belong to the class called multiple loop nonlinear feedback systems. In the long history of human evolution, it has not been necessary for man to understand these systems until very recent historical times. Evolutionary processes have not given us the mental skill needed to interpret properly the human behaviour of the systems of which we have now become a part." Forrester (1973, p.5).

Chapter 7

A Dynamic General Equilibrium-*Seeking* Model for a 'Closed' Economy

7.1 Introduction

The general equilibrium theory of the competitive market economy, originating from Léon Walras (1954)[124] and the extensional work of particularly Kenneth Arrow and Gérard Debreu (Arrow, 1951; Debreu, 1951, 1959; Arrow and Debreu, 1954),[125,126] has provided us with fundamental insights into the factors and mechanisms determining relative prices, resource allocation, and income distribution within and between economies. Computable General Equilibrium (CGE) models are an attempt to use general equilibrium theory within a numerical framework for assessment of economic policies. Starting with Johansen's pioneering (1960) multi-sectorial study of economic growth, and aided by rapid advances in computer technology,[127] CGE models are now a standard item in the toolbox of economists concerned with policy-oriented research. By design, CGE models are focused on describing steady states of economic equilibrium, usually following an exogenous policy intervention or economic 'shock'. This has included *inter alia* analysis of major tax reforms; development issues;

[124] An English translation of Walras' main work *Eleménts d'économie politique pure*, first published 1874-77.

[125] Walras formulated the state of the economic system as the solution of a system of simultaneous equations representing the demand for goods by consumers and the supply of goods by producers, assuming that consumers act so as to maximise utility, producers act so as to maximise profits and perfect conditions prevail. Arrow and Debreu provided formal mathematical proofs of the existence of such equilibrium for a competitive economy.

[126] We should also acknowledge the significant contribution of von Neumann's 1932 Princeton seminar on balanced economic growth (von Neumann, 1937). Unlike many other models of general equilibrium at the time, von Neumann's model specifically took into the account the possibility for several commodities to be produced by a single economic process, and for multiple processes to be responsible for the production of a single commodity. In order to deal with the situation of more unknown variables than equations, von Neumann formulated the equilibrium conditions as a complementarity problem, and introduced the 'Rule of Free Goods' and the 'Rule of Idle Activities'. Although Zeuthen (1993) and Schlesinger (1935) had also put forward the use of the Rule of Free Goods to avoid negative prices, von Neumann was the first to formulate duality and complementary slackness conditions in a symmetric, fully specified model (Zalai, 2003).

[127] The literature generally attributes the emergence of CGE modelling also to Harberger's (1962) analysis of tax policies, and Scarf's (1967) and Scarf and Hansen's (1973) work on conditions for the existence of and algorithms for computation of Walrasian equilibria.

changes in trade, agriculture, energy and environmental policy; and assessment of major-projects and events.[128]

Despite the widespread popularity of CGE modelling, the approach is frequently criticised for its inadequacy in dealing with time-path trajectories and out-of-equilibrium dynamics (Barker, 2004; Grassini, 2004; Scrieciu, 2007). Economies do not tend to be characterised by steady states of equilibrium,[129] but are rather subject to a never-ending process of dynamic disequilibrium (Soros, 1990). Against this dynamic backdrop, and especially where policy options under consideration must be implemented progressively rather than instantaneously, policy analysts struggle to interpret and apply the information obtained from CGE models in real world decision-making. Although dynamic CGE models have been a major research focus for at least 20 years, their development is still very much ongoing. On the one hand, there are models that determine an optimal pathway for economic adjustment by *simultaneously* determining equilibrium at a number of points in time for a given study period. While this may result in 'smoother' adjustment paths (Zodrow and Diamond, 2013), it implicitly assumes that agents (e.g. households, businesses, government) have perfect foresight. On the other hand, the more common recursive dynamic CGE models assume *inter alia* agents have myopic expectations, with equilibria determined *sequentially*. Under both approaches, the outcome sequence linking two equilibria is typically never explained, and the length of time it takes to transition between equilibria, although unknown, is usually assumed to be a year. The optimisation or mathematical programming approach often deployed in CGE modelling is also problematic when, as in this thesis, the economy is considered part of a wider integrated environment-economy system. The latter is not characterised by a predetermined objective function or functions (as per a standard CGE model), but rather by dynamic feedbacks, non-linearities, and time lags. These characteristics are difficult to consider when time is not explicitly accounted for in modelling.

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[128] Other examples may be found in Shoven and Whalley (1984, 1992), Ginsburgh and Keyser (1997), Rose and Liao (2005), Bergman (2005), and Partridge and Rickman (1998, 2010).

[129] For the purposes of this chapter, economic equilibrium is defined as a system state in which physical quantities (includes levels of production by industries, the production and use of commodities) changes by some constant rate. Depending on whether this rate is zero, positive or negative, the economy may stagnate, increase or decline. When one takes into consideration the finite nature of environmental systems, and the essential provision of goods and services by the environment to economic systems, the idea of an economy that can consistently grow in physical size becomes highly questionable. Nevertheless, this does not preclude the possibility of economic systems that continuously 'seek' or 'strive' towards an equilibrium state, even if the actual nature of the equilibrium state sought must also change continuously to reflect in part changing environmental conditions.

In this chapter, a novel Dynamic General Equilibrium-*Seeking* (DGES) model of a closed[130] economy is developed, which explicitly considers the transition pathway taken by an economy in seeking equilibrium, using the Vensim® DSS System Dynamics software. Note that this model is further operationalised by inclusion as the core economic components of the global environment-economy model 'Ecocycle' described within Chapter 9.

The chapter develops the DGES model in stages. First, Section 7.2 describes the key underlying dynamics controlling price change within a System Dynamics framework. These dynamics are essential to the regulation of the entire economic system and are replicated several times within the model for various commodities and factors. Second, Section 7.3 sequentially develops two versions of the model. Using the self-regulating price mechanism developed in Section 7.2, Section 7.3.1 translates a standard CGE model[131] into the System Dynamics language (the DGES constant factor or 'DGES CF' model). 'Shocking' this model will generate, over the long run, an equilibrium that is identical[132] to a standard optimisation or mathematical programming-based CGE model. The key difference, however, is that this model depicts the transition pathway taken through time in reaching equilibrium. Despite this model including time in its formulation, it cannot truly be considered a dynamic model, as key economic stocks are held constant over a model run. Section 7.3.2 further develops the model by incorporating labour and capital factor stocks (the DGES growth factor or 'DGES GF' model). Finally, Section 7.4 describes the dynamic behaviour of the various models developed through a few stylised exogenous shocks.

The Vensim® DSS models created in this chapter may be found in the Chapter 7 directory of the accompanying CD-ROM. The program code for the models, DGES CF.txt and DGES GF.txt, are also contained within this directory.

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[130] The term 'closed' is used here simply to infer that there exists no external trade with economies outside the subject system (e.g. imports and exports of commodities, foreign inputs of capital). This is an appropriate approach, given the *global* scale of the selected economic system. However, as explained in Chapter 3, the economic system is not actually conceived as closed in a physical sense, as there are numerous flows of mass/energy with the environment.

[131] Refer to Lofgren *et al*. (2002) for a detailed specification of a standard CGE model.

[132] A CGE model run will typically produce an equilibrium that satisfies a set of budgetary constraints within a specified *tolerance*. The DGES model instead oscillates *ad infinitum* towards equilibrium.

7.2 Representing Supply, Demand and Price in a System Dynamics Model

A central idea put forward in any introductory economic textbook is that in competitive economies, prices enable markets to adjust to a point of equilibrium, where the supply of a particular good or service is in balance with the demand for that good or service. The role of a CGE model is to depict numerically such a 'world', where a balance between supply and demand is attained through relationships between price and supply/demand. This, however, presents a relatively static view of demand-supply relationships, providing no information on the processes through which equilibrium is reached. The key task in translating a standard CGE model from an optimisation or mathematical programming problem into a System Dynamics simulation model is explicit inclusion of the relationships between supply, demand, and price that cause economic systems to adjust to a state of equilibrium.

When modelling a supply, demand, and price system, many System Dynamists (e.g. Low (1974), Mass (1980), Whelan and Msefer (1996), Sterman (2000)) suggest that it is the inventory of a particular commodity, as well as the actual rate of commodity supply and demand, that affects the market price for that commodity. Their reasoning is that even if manufacturers supply goods at a rate equal to that of consumer demand, if there is a large surplus of goods in stock, the price of the goods will reduce to increase the willingness and ability of buyers to purchase goods, thus helping to return inventories to desired levels. A lowering of the average market price for the good will, in turn, have an opposite impact on other sellers, reducing their ability to supply goods and thus also helping to return inventories to desired levels. These relationships are depicted in the causal loop diagram in Figure 7.1 below.[133]

Causal loop diagrams such as Figure 7.1 are key tools used in System Dynamics to represent relationships among sets of variables operating in a system (refer, for example, to Sterman (2000) and Maani and Cavana (2007)). An arrow linking two variables is used here to indicate a causal association between those variables. A '+' symbol adjacent to the arrow indicates that an increase in the variable at the tail of the arrow causes a corresponding increase in the variable at the head of the arrow, above what it would have been otherwise. Conversely, a '–' symbol indicates that, compared with a situation with no change, a change in the tail variable causes the head variable to change in the opposite direction. Note that there are two types of

[133] In this chapter, 'supply' and 'production' are used interchangeably, as are 'demand' and 'consumption'.

feedbacks or causal loops created by this relatively simple set of relationships between supply, demand, and price. In both cases, the feedback loop is 'negative' or 'balancing' (represented by the two negative symbols at the centre of the Figure 7.1), meaning that a directional change in an initial variable will ultimately cause a change in the opposite direction for that same variable. Importantly, it is the presence of at least one dominant balancing feedback loop in a system that acts to counter system disturbances or shocks, leading the system ultimately back towards some type of steady state or goal. As will be seen, the modelling of general equilibrium as a dynamic system essentially involves the establishment of a number of these price-related balancing feedback loops.

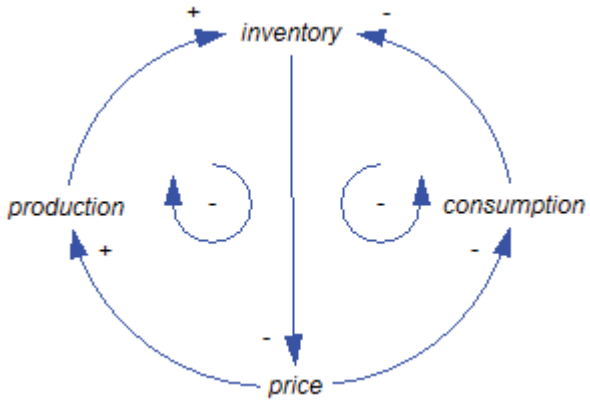

Figure 7.1 **Relationships between Commodity Production, Consumption, and Price**

Figure 7.2 now depicts the detail of the causal mechanisms shown in Figure 7.1 above between inventory and price. A key point to note is the central role of the stock variable $Inventory_i$, which defines the available quantity of commodity i at any given point in time,[134] in formulating the supply-demand forces that affect price movements. 'Stocks'[135] (the first letter of any stock variable is capitalised) are used in System Dynamics models where it is necessary to represent a system variable that accumulates over time. A further feature of a stock is that it will continue to exist even if all inflows to, and outflows from, the stock cease to exist. By contrast, 'flows'[136] (represented solely by lowercase letters) record material or information exchanges to, or from, a stock (e.g. *productionc*, *usec*, and *changepcoms* in Figure 7.2 below), and cannot be observed at a single point in time except by accumulation or averaging.

[134] For many non-physical commodities (e.g. hairdressing and legal services) it is more relevant to use a demand measure for the 'inventory' stock rather than a supply measure – for example, the number of orders waiting to be fulfilled.
[135] Also referred to as 'levels' or 'state variables'.
[136] Also referred to as 'fluxes' or 'rates'.

Converters[137] (also represented by lowercase letters) are used to disaggregate the complex functions that define flows into their constituent parts (e.g. *inventoryratio*, *desiredinventory*, *effectpcoms*, and *desiredpcoms* in Figure 7.2). Finally, constants (represented by uppercase letters) are special types of converters defined by a function that is either constant or only time dependent. These are defined exogenous to the model e.g. *LOOKUPPCOMS*, *CDPCOMS*, and *INVENTHORIZ*.

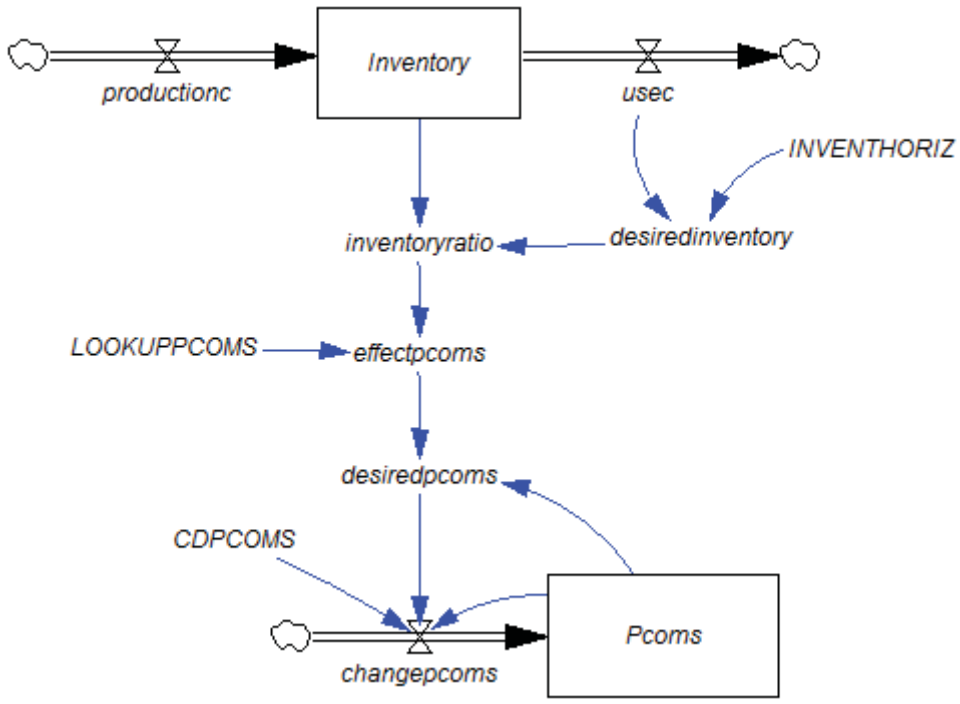

Figure 7.2 Inventory-Price Stock-Flow Diagram for Commodities

Notes: *CDPCOMS* = change delay for commodity price, *changepcoms* = increase in commodity price, *desiredinventory* = desired commodity stock, *desiredpcoms* = desired commodity price, *effectpcoms* = commodity price change effect, *INVENTHORIZ* = desired periods of commodity supply held in stock, *Inventory* = commodity stock, *inventoryratio* = ratio of commodity stock to desired commodity stock, *LOOKUPPCOMS* = lookup function determining applicable price change effect, *Pcoms* = commodity supply price, *productionc* = commodity production, *usec* = commodity use. Adapted from Whelan and Msefer (1996).

Despite the distinction between stock and flow variables being well recognised in economics, economic analysis is predominated only by flow concepts of supply and demand (Low, 1980; Mass, 1980). Largely this is a reflection of theories of the household and the firm having evolved out of the equilibrium ideas respectively of profit and utility maximisation. At equilibrium, where profits and utility are maximised, inventories held by firms and households are at constant desired levels and like other similar stock concepts, tend to be given little consideration. Nevertheless, it is important to recognise that stocks can continue to fluctuate,

[137] Also referred to as 'auxiliaries'.

even when flows (supply and demand) appear to be relatively stable (Mass, 1980). Thus, accurate representation of the dynamic behaviour of economic systems requires explicit consideration of both stock and flow variables and any associated interrelationships.

In addition to $Inventory_i$, the supply price of commodity i, $Pcoms_i$, is represented as a stock variable. The use of stocks for modelling prices is necessary because markets do not determine prices instantaneously; rather the process of price adjustment is gradual, with each period building upon the previous. Both of the stock variables, $Inventory_i$ and $Pcoms_i$, are defined by finite difference equations:

$$Inventory_i(t+dt) = Inventory_i(t) + (productionc_i - usec_i) \times dt \text{ , and} \quad (7.1)$$

$$Pcoms_i(t+dt) = Pcoms_i(t) + changepcoms_i \times dt \text{ .} \quad (7.2)$$

The flows $productionc_i$ and $usec_i$ in Eq. 7.1 are, respectively, the quantities of commodity i produced and consumed during the period (i.e. dt), while $changepcoms_i$ in Eq. 7.2 is the period increase in supply price for commodity i.

Assuming that the greater the economy-wide demand for commodity i, the greater the desired level of stock on hand, the desired inventory level is set as a linear relationship between commodity demand and an exogenous inventory horizon, $INVENTHORIZ_i$. This latter constant is the number of periods over which the stock of inventory could meet demand, not accounting for new production. Thus,

$$desiredinventory_i = usec_i \times INVENTHORIZ_i \text{ .}$$

The greater the relative difference between the desired inventory and the actual inventory, the greater the relative price change occurring within the model. This mechanism is implemented through Eqs. 7.3–7.6 below. The term $LOOKUPPCOMS_i$ in Eq. 7.4 is an exogenous lookup function that determines the relative price change effect, depending on the relative difference in actual and desired inventories. Where the desired inventory is less than the actual inventory, and thus $inventoryratio_i$ is greater than one, the function returns a value less than one causing price to decrease. The opposite occurs where $inventoryratio_i$ is less than

one.[138] The exogenous price change delay variable, $CDPCOMS_i$, is a scalar set between 0 and 1.[139]

$$inventoryratio_i = \frac{Inventory_i}{desiredinventory_i} \tag{7.3}$$

$$effectpcoms_i = LOOKUPPCOMS_i\left(inventoryratio_i\right) \tag{7.4}$$

$$desiredpcoms_i = Pcoms_i \times effectpcoms_i \tag{7.5}$$

$$changepcoms_i = \frac{\left(desiredpcoms_i - Pcoms_i\right)}{CDPCOMS_i} \tag{7.6}$$

7.3 Description of the Dynamic General Equilibrium-*Seeking* Model

7.3.1 The Dynamic General Equilibrium-*Seeking* Model with Constant Factors

For exposition purposes, the model is separated into six modules: commodities, industries, factors, government, investment and savings, and households. Each of the modules is described in detail below.

Commodities Module

Figure 7.3 provides a graphical representation of the commodities module. Note that the causal structure for any variable contained within parentheses (i.e. '< … >') is either defined in another module or exists elsewhere within the same module, and that a number of the equations for the commodities module have already been explained above. For simplicity, the model is structured on the basis that each economic activity or industry, denoted by subscript *j*, produces only one homogenous commodity,[139a] thus,

$$productionc_i = productionf_j \;\; \forall \; i = j \,,$$

where $productionc_i$ and $productionf_j$ are, respectively, the total production of commodity i output and the total quantity of industry j output. Similarly,

[138] Empirical analysis that assists in determining appropriate shapes for these curves is likely to be a focus in the further development of this model.

[139] Although the price change delay constants are all set at a default value of 1 in the example model below, it is possible to alter the rate at which price changes occur through use of these variable types.

$$pinds_i = Pcoms_j \ \forall \ i = j \ ,$$

where, as above, $Pcoms_i$ is the supply price for commodity i and $pinds_j$ is the supply price of industry j output. This approach means that the base year data used to populate the model (i.e. the within economy matrices of the ESAM) must be formulated so that the commodities definitions exactly match the industry definitions, and furthermore only one type of commodity is produced by each industry. The required form can be achieved by applying the method set out in Section B.2.2 of Appendix B.[140]

The majority of the variables shown in the lower half of Figure 7.3 are already explained in Section 7.2. One should also note, however, the addition of an exogenous industry production tax rate, $TAXPRODF_j$, which creates a wedge between the commodity supply price, $Pcoms_i$, and commodity demand price, $pcomd_i$ (Eqs. 7.7 and 7.8 respectively).

$$pcomd_i = Pcoms_i \left(1 + taxprodc_i\right) \tag{7.7}$$

$$taxprodc_i = TAXPRODF_j \ \forall i = j \tag{7.8}$$

[140] This method allows for generation of symmetric tables, selecting a combination of CTA and ITA, as appropriate to the system under consideration.

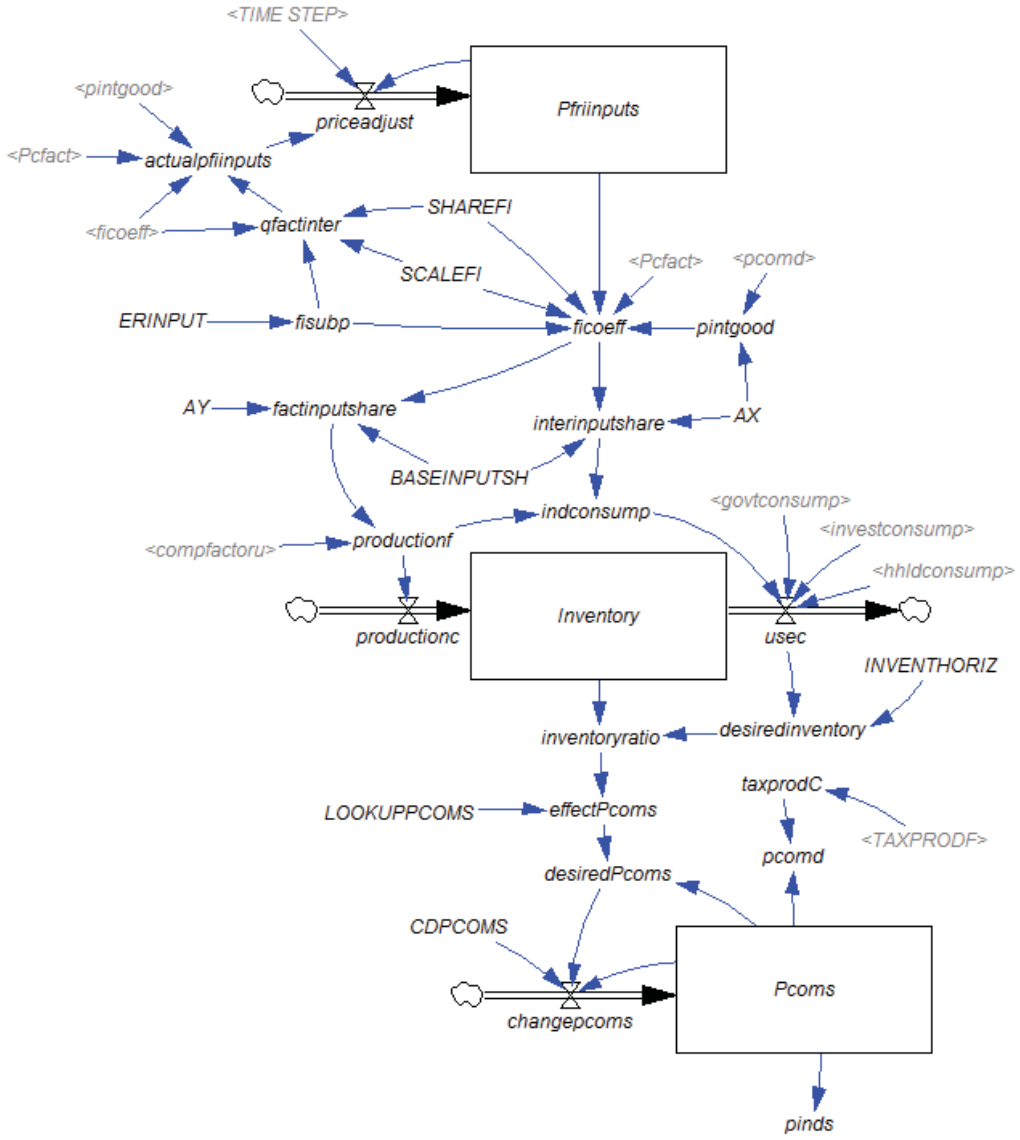

Figure 7.3 Commodities Module Influence Diagram

Notes: *actualpfiinputs* = calculated price for composite inputs supplied, *AX* = base year commodity input coefficient, *AY* = base year factor input coefficient, *BASEINPUTSH* = base year factor/intermediate input coefficient, *CDPCOMS* = change delay for commodity price, *changepcoms* = increase in commodity price, *compfactoru* = use of composite factors, *desiredinventory* = desired commodity stock, *desiredpcoms* = desired commodity price, *effectpcoms* = commodity price change effect, *ERINPUT* = elasticity of factor-intermediate inputs substitution, *factinputshare* = factor inputs per unit of production, *ficoeff* = total factor/intermediate inputs coefficient, *fisubp* = factor-intermediate inputs substitution parameter, *INVENTHORIZ* = desired periods of commodity supply held in stock, *govtconsump* = government consumption, *hhldconsump* = household consumption, *indconsump* = intermediate consumption, *interinputshare* = commodity inputs per unit of production, *Inventory* = commodity stock, *inventoryratio* = ratio of commodity stock to desired commodity stock, *investconsump* = investment consumption, *LOOKUPPCOMS* = lookup function determining applicable price change effect, *pcfact* = composite factor price, *pcomd* = commodity demand price, *Pcoms* = commodity supply price, *Pfriinputs* = composite input price, *pinds* = industry output price, *pintgood* = composite intermediate input price, *priceadjust* = adjustment to composite input price, *productionc* = commodity production, *productionf* = industry production, *qfactinter* = quantity of composite inputs supplied, *SCALEFI* = scale parameter for factor-intermediate inputs substitution, *SHAREFI* = share parameter for factor-intermediate inputs substitution, *taxprodc* = commodity production tax rate, *TAXPRODF* = industry production tax rate, *usec* = commodity use.

The quantity of output produced by each industry is calculated in a manner similar to the nested constant elasticity of substitution (CES) functions applied in most CGE models. To begin, the quantity of output produced by each industry, $productionf_j$, is determined by the use of composite factors by that industry, $compositefactoru_j$, relative to the ratio of factor inputs per unit of production, $factinputshare_j$ (Eq. 7.9). The quantity of composite factors used by an industry, in turn, is a combined measure of the labour and capital endowments of that industry (refer to the factors module). For simplicity, many static CGE models assume that there is no substitution between intermediate goods and composite factors, and thus $factinputshare_j$ is set equal to a factor input coefficient AY_j, defined by the base year ratio of the quantity of composite factors required, per unit of production by industry j. This model, however, allows for the possibility of substitution between intermediate goods and composite factors. Thus, $factinputshare_j$, can adjust to reflect new estimates of the ratio of factor inputs (FactsI) per unit of production, $ficoeff_{j,\mathrm{FactI}}$, where $BASEINPUTSH_{j,\mathrm{FactI}}$ refers to the base year value of $ficoeff_{j,\mathrm{FactI}}$ (Eq. 7.9).

Revised industry coefficients for both factors and total intermediate goods (InterI), $ficoeff_{j,\lambda}$ ($\lambda \in \{\mathrm{FactsI}, \mathrm{InterI}\}$) are determined via a CES function (Eqs. 7.11 and 7.12). Importantly, the share of total inputs attributed to either factors or intermediate goods is controlled by the relative price of that input, $Pcfact_j$ or $Pintgoods_j$ respectively, along with the converter $ifsubp_j$, specifying the degree of substitution between inputs. The latter converter, in turn, is determined by the elasticity of substitution between factors and intermediate goods, $EFIINPUT_j$ (Eq. 7.13). The price of composite factor inputs, $Pcfact_j$, is defined under the factors module, while the price of intermediate goods for an industry j, $Pintgoods_j$, is a weighted average of the prices of all commodities required by that industry (Eq. 7.14). In these regards the constant $AX_{i,j}$ defines the quantity of commodity i required per unit of production by industry j at the base year. The constants $SCALEFI_j$ and $SHAREFI_{j,\lambda}$ appearing within Eqs. 7.11 and 7.12 are, respectively, the CES function scale and share parameters.

$$productionf_j = \frac{compositefactoru_j}{factinputshare_j} \tag{7.9}$$

$$factinputshare_j = AY_j \times \frac{ficoeff_{j,\mathrm{FactI}}}{BASEINPUTSH_{j,\mathrm{FactI}}} \tag{7.10}$$

$$ficoeff_{j,\mathrm{FactI}} = \left(\frac{SCALEFI_j^{\,ifsubp_j} \times SHAREFI_{j,\mathrm{FactI}} \times Pfiinputs_j}{Pcfact_j} \right)^{\left(\frac{1}{1-ifsub_j}\right)} \tag{7.11}$$

$$ficoeff_{j,\text{InterI}} = \left(\frac{SCALEFI_j^{\,ifsubp_j} \times SHAREFI_{j,\text{InterI}} \times Pfiinputs_j}{Pintgoods_j} \right)^{\left(\frac{1}{1-ifsub_j}\right)} \tag{7.12}$$

$$fisubp_j = \frac{EFIINPUT_j - 1}{EFIINPUT_j} \tag{7.13}$$

$$pintgood_j = \frac{\sum_i \left(AX_{i,j} \times pcomd_i \right)}{\sum_i AX_{i,j}} \tag{7.14}$$

In order for the CES function to effectively allocate total input requirements for each industry among factors and intermediate goods, it is essential that the price of combined factor and intermediate goods for each industry as appearing within Eqs. 7.11 and 7.12, $Pfiinputs_j$, varies across time to reflect the relative price changes in those inputs. This is achieved in the model by continuously adjusting $Pfiinputs_j$ so it is consistent with the actual price calculated for combined commodity and factor inputs for each industry (Eqs. 7.15–7.18). Note that multiplication by the inverse of the time step, $TIMESTEP$, is necessary within Eq. 7.16 to ensure that the necessary price adjustment occurs immediately. The converter $qfactinter_j$ represents the actual proportion of inputs that would be supplied to an industry j based on the factor and intermediate goods shares calculated under Eqs. 7.10 and 7.11.

$$Pfiinputs_j\left(t + dt\right) = Pfiinputs_j\left(t\right) + priceadjust_j \times dt \tag{7.15}$$

$$priceadjust_j = \left(actualpfiinputs_j - Pfiinputs_j \right) \times \left(\frac{1}{TIMESTEP} \right) \tag{7.16}$$

$$actualpfiinputs_j = \frac{ficoeff_{j,FAC} \times Pcfact_j + ficoeff_{j,INT} \times pintgood_j}{qfactinter_j} \tag{7.17}$$

$$qfactinter_j = SCALEFI_j \times \left(\sum_\lambda \left(SHAREFI_{j,\lambda} \times ficoeff_{j,\lambda}^{\,ifsubp_j} \right) \right)^{\left(\frac{1}{ifsubp_j}\right)} \tag{7.18}$$

Having dealt with the supply side of commodities, total commodity demand is determined by the sum of household, government and investment/savings demand, as well as commodities required by industries themselves (Eq. 7.19). The quantity of a selected commodity i required for production within a given industry j, $indconsump_{i,j}$, is determined by first adjusting the fixed input coefficient for the base year, $AX_{i,j}$ to reflect any substitution between intermediate goods and factor inputs to arrive at revised input coefficients, $interinputshare_{i,j}$ (Eq. 7.20).

Note that the constant $BASEINPUTSH_j$ defines the value of $ficoeff_{j,\text{IntI}}$ at the base year. Next, $indconsump_{i,j}$ is calculated simply by multiplying the output of each industry by its new input coefficient (Eq. 7.21).

$$usec_i = \sum_j indconsump_{i,j} + govtconsump_i + investconsump_i + hhldconsump_i \quad (7.19)$$

$$interinputshare_{i,j} = AX_{i,j} \frac{ficoeff_{j,\text{int}}}{BASEINPUTSH_j} \quad (7.20)$$

$$indconsump_{i,j} = productionf_j \times interinputshare_{i,j} \quad (7.21)$$

Industries Module

The industries module of the model is described in Figure 7.4. The stock shown at the top of the figure, $Industryaccount_j$, records accumulated profits generated by each industry as a result of that industry's income from sales, $salesf_j$, less total expenditure incurred, $indexpends_j$ (Eq. 7.22). Following the zero profit condition as normally applied in a CGE model, each industry seeks to clear its available funds through production expenditure, thus tending towards no net profit. Hence desired industry expenditure, $indexpendd_j$, is set equivalent to the available funds in the industry account (Eq. 7.23). Because supply, demand, and price are always transitioning toward a point of equilibrium in model, there may be time periods for which $indexpends_j$ (Eq. 7.24) vary from $indexpendd_j$.

Assuming constant returns to scale as per the standard CGE model, the desired level of production for each industry can now be calculated by dividing total desired industry expenditure by the costs involved in producing one unit of industry output, $unitcostprod_j$. Next, multiplying by the composite factor input coefficient, $factinputshare_j$, determines each industry's total demand for composite factors (Eq. 7.25). The $unitcostproduction_j$ variables are, in turn, calculated simply according to each industry's input coefficients and the respective prices for composite factors, $Pcfact_j$, and intermediate goods, $pcomd_i$ (Eq. 7.26).

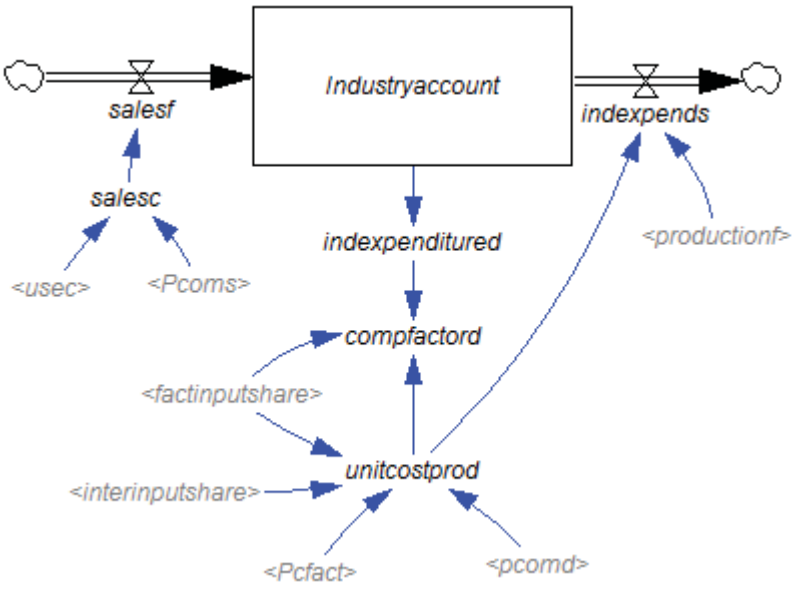

Figure 7.4 Industries Module Influence Diagram

Notes: *compfactord* = composite factor demand, *factinputshare* = factor inputs per unit of production, *indexpenditured* = available industry expenditure, *indexpends* = actual industry expenditure, *Industryaccount* = industry account, *interinputshare* = commodity inputs per unit of production, *Pcfact* = composite factor price, *pcomd* = commodity demand price, *Pcoms* = commodity supply price, *salesc* = commodity sales, *salesf* =industry sales, *unitcostprod* = unit cost of production, *usec* = commodity use.

$$Industryaccount_j(t+dt) = Industryaccount_j(t) + (salesf_j - indexpends_j) \times dt$$

where:

$$Industryaccount_j(0) = indexpends_j(0) \quad (7.22)$$

$$indexpendd_j = Industryaccount_j \quad (7.23)$$

$$indexpends_f = unitcostprod_f \times production_f \quad (7.24)$$

$$compositefactord_j = \frac{indexpendd_j}{unitcostprod_j} factinputshare_j \quad (7.25)$$

$$unitcostprod_j = factinputshare_j \times Pcfact_j + \sum_i (interinputshare_{i,j} \times pcomd_i) \quad (7.26)$$

Factors Module

Figure 7.5 describes the factors module. The factors module simulates, given total available supplies of labour and capital, the relative demand and supply of these factors to industries, and the dynamics of factor price changes.

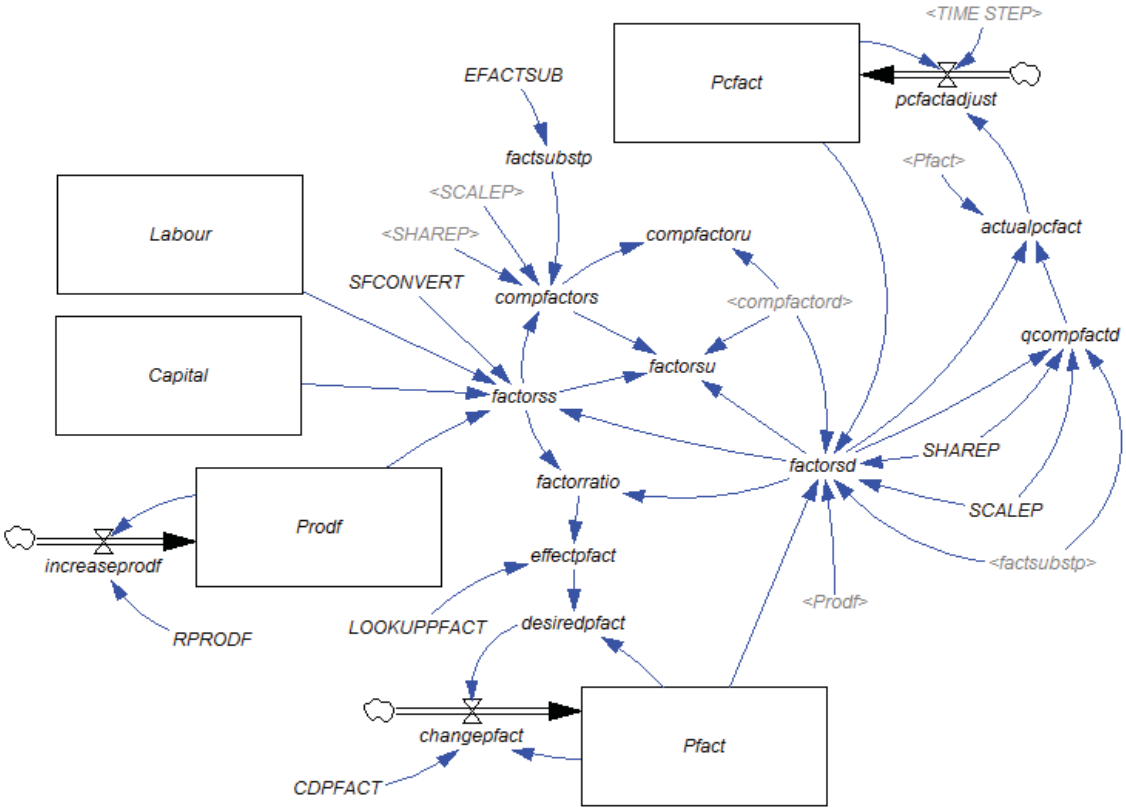

Figure 7.5 Factors Module Influence Diagram

Notes: *actualpcfct* = calculated composite factor price, *Capital* = capital stock, *CDPFACT* = change delay for factor price, *changepfact* = increase in factor price, *compfactord* = composite factor demand, *compfactors* = composite factor supply, *desiredpfact* = desired factor price, *effectpfact* = factor price change scalar, *EFACTSUB* = elasticity of factor substitution, *factorsd* = demand for factors, *factorratio* = ratio of factor supply to demand, *factorss* = supply of factors, *factorsu* = use of factors, *factsubstp* = factor substitution parameter, *increaseprodf* = increase in productivity, *Labour* = labour stock, *LOOKUPPFACT* = lookup function for factor price change scalar, *Pcfact* = composite factor price, *pcfactadjust* = adjustment to composite factor price, *pfact* = factor price, *Prodf* = factor productivity scalar, *qcompfactd* = calculated composite factor demand, *RPRODF* =rate of productivity increase, *SCALEP* =share parameter for factor substitution, *SHAREP* = share parameter for factor substitution, *SFCONVERT* = stock-flow converter.

There are two sets of price stocks contained within the module, $Pcfact_j$ and $Pfact_{h,j}$. While the former defines an average total (i.e. 'composite') factor price for industry j, taking account of the relative supplies of labour and capital to that industry and the respective prices of those factors, the latter is a specific price for factor h within industry j. The price stocks $Pfact_{h,j}$ vary in response to relative differences in the supply of factor h to industry j, and the demand for factor h by that industry, $factorss_{h,j}$ and $factorsd_{h,j}$. The mechanisms through which these price change dynamics are implemented are analogous to those explained in Section 7.2 (for the corresponding factor module equations refer to Eqs. F.1–F.5 in Appendix F).[141]

[141] Note also that the model is set up such that where a particular factor is mobile across industries, $Pfact_{h,j}$ will be uniform for across all j industries.

The producers within the economy (represented by industries) generate economic outputs subject to their production technologies. The technologies defining inputs of intermediate goods and composite factors are explained under the commodities module. Moving now to the next layer of the production nest, the technologies underpinning composite factor 'supply' within each industry, $compfactors_j$, are represented by CES functions consisting of labour and capital factor endowments (Eq. 7.27). The $factsubstp_j$ parameters in these CES functions are exogenously derived elasticities of substitution between the labour and capital factor inputs, $EFACTSUB_j$ (Eq. 7.28), while $SCALEP_j$ and $SHAREP_{h,j}$ are, respectively, CES function scale and share parameters.[142]

$$compfactors_j = SCALEP_j \times \left(\sum_h \left(SHAREP_{h,j} \times factorss_{h,j}^{\,factsubstp_j} \right) \right)^{\frac{1}{factsubstp_j}} \tag{7.27}$$

$$factsubstp_j = \frac{EFACTSUB_j - 1}{EFACTSUB_j} \tag{7.28}$$

The factors module also incorporates an ability to include exogenous technological change; leading to improved efficiency in the utilisation of labour and capital endowments. This is incorporated by way of productivity stocks for each factor h, $Prodf_h$, which grow in accordance with an exogenous rate of productivity growth, $RPRODF_h$ (Eqs. 7.29 and 7.30).

Recalling that this section is focused on the translation of a *static* CGE into a System Dynamics framework, the total stocks of capital and labour are for exposition purposes temporarily set as constant exogenous values.[143] Note that when undertaking a general equilibrium analysis, factor stocks are typically set as either fixed to certain industries (i.e. immobile) or free to move between industries (i.e. mobile), depending on the length of time for the analysis. Where, for example, the focus of a study is just on short-term impacts, the amount of capital held by each industry will typically be considered fixed, given that capital items (buildings, machinery, etc.) are not easily switched between uses. In replicating a standard CGE model the stock of capital is assumed immobile, while labour is assumed mobile. Stocks of capital are therefore defined specific to industries, $Capital_j$, while the labour stock, $Labour$, has no subscripts. The effective supply of capital to each industry can now be determined simply by multiplying available capital stocks by the variables $Prodf_{cap}$ and $SFCONVERT_{cap}$ (Eq. 7.31).

[142] Refer, for example, to Hosoe *et al*. (2010) for further explanation of these parameters.
[143] This requirement is relaxed in Section 7.3.2 enabling the DGES to be formulated.

The purpose of the latter variable is to convert capital, thus far measured as a stock, into a flow measure of capital. A similar approach is also taken to convert the labour stock into industry labour endowments (Eq. 7.32).[144] However, this time, because labour is mobile across industries, the total supply of labour must also be shared among industries according to each industry's relative demand.

$$Prodf_h(t+dt) = Prodf_h(t) + increaseprodf_h \times dt$$
where: (7.29)
$$Prodf_h(0) = 1$$

$$increaseprodf_h = Prodf_h \times RPRODF_h \quad (7.30)$$

$$factorss_{cap,j} = Capital_j \times SFCONVERT_{cap} \times Prodf_{cap} \quad (7.31)$$

$$factorss_{lab,j} = Labour \times SFCONVERT_{lab} \times Prodf_{lab} \times \frac{factorsd_{lab,j}}{\sum_j factorsd_{lab,j}} \quad (7.32)$$

Turning now to the demand-side of the module, following the principle of profit maximisation, industries will choose to utilise a combination of labour and capital inputs that meet the required total 'production' level of composite factors, while minimising costs. Just like the approach described above to determine the relative input of factors versus intermediate goods, the first-order conditions for this problem enables a function to be generated that specifies each industry's desired consumption of primary factors, given relative differences in factor price (Eq. 7.33). Also like in the commodities module, it is necessary to continuously update the composite price (this time for composite factors, $Pcfact_j$) to enable the CES function to effectively allocate total factor input demands among labour and capital. Adjustments to the composite factor occur in an analogous manner to that described within the commodities module (refer to Eqs. F.6–F.9 in Appendix F).

$$factorsd_{h,j} = \left(\frac{SCALEP_j^{\,factsubstp_j} \times SHAREP_{h,j} \times Pcfact_j}{Pfact_{h,j}} \right)^{\frac{1}{1-factsubstp_j}} \times compfactd_j \quad (7.33)$$

The converter $compfactoru_{,j}$ (already mentioned under the commodities module above) defines the actual consumption of composite factors by industry j. Note that $compfactoru_j$

[144] The stock may be measured by the number of available workers (with each worker exhibiting a capacity to work a certain number of hours each week), while the flow measure might be the actual supply of working hours over a week.

may vary from the desired consumption of composite factors by industry j, $compfactord_j$, where the supply of composite factors to the industry is insufficient to meet demand. Composite factor use can also vary from supply, $compfactors_j$, where there is an over-supply or surplus (Eq. 7.34). It is further necessary to define the quantities of each factor actually used by each industry, $factorsu_j$, as these values feed into the income and tax calculations under the household and government modules, respectively (Eq. 7.35).

$$compfactoru_j = \min\left(compfactors_j, compfactord_j\right) \ \forall j \tag{7.34}$$

$$\begin{aligned} factorsu_{h,j} &= factorsd_{h,j}, \text{ s.t. } compfactors_j \geq compfactord_j \\ factorsu_{h,j} &= factorss_{h,j}, \text{s.t } compfactors_j < compfactord_j \end{aligned} \tag{7.35}$$

Government Module

A relatively straightforward approach is taken in the construction of the government module (Figure 7.6). A single stock, *Govtaccount*, keeps track of available government funds, receiving additions of disposable government income, *govtincome*, and subtractions from government expenditure, *govtexpend* (Eq. 7.36).

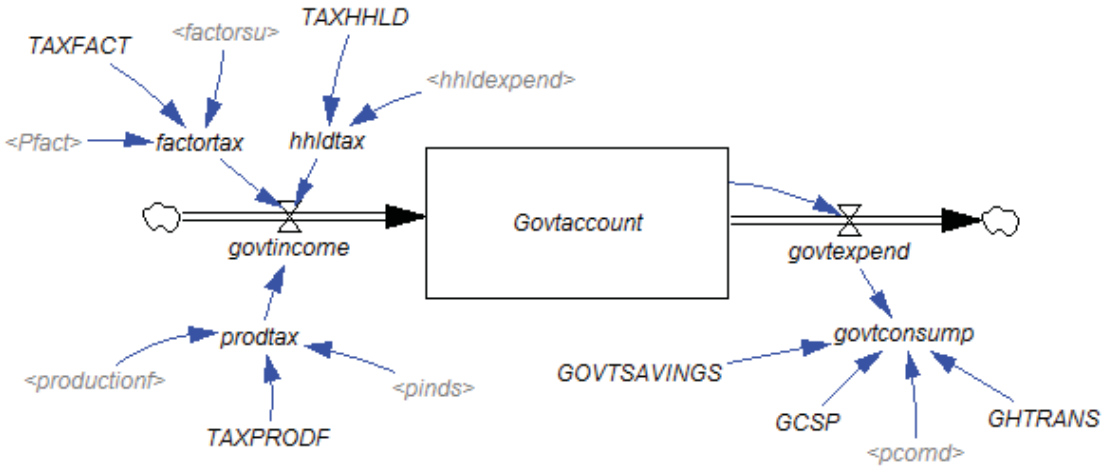

Figure 7.6 Government Module Influence Diagram

Notes: *factorsu* = factor use, *GCSP* = government consumption commodity share, *GHTRANS* = government to households transfers, *Govtaccount* = government account, *govtconsump* = government consumption, *govtexpend* = government expenditure, *govtincome* = government disposable income, *GOVTSAVINGS* = government savings, *hhldexpend* = household expenditure, *hhldtax* = household taxes, *pcomd* = commodity demand price, *Pfact* = factor price, *pinds* = industry output price, *prodtax* = production taxes, *productionf* = industry production, *TAXFACT* = factor tax rate, *TAXHHLD* = household tax rate, *TAXPRODF* = industry tax rate.

The value of *govtincome* is determined by the sum of the various taxes received. The underlying SAM (or, in the case of this thesis, the within economy matrices of the ESAM) will normally determine the types of taxes that need to be included. The relevant taxes are on factors, *factortax*, production, *prodtax*, and household consumption, *hhldtax*. Eqs. 7.38–7.40 determine the total values received respectively from each of these taxes. Three sets of exogenous tax rates are used in these equations, $TAXPRODF_j$, $TAXFACT_h$ and *TAXHHLD*. These respectively represent the production tax rate, factor tax rate, and household consumption tax rate. The converter *hhldexpend* captures the total expenditure by households on consumption of goods and services and is defined under the households module. The remaining variables are already explained above.

In constructing the government module, there is a reasonable amount of discretion available in the choice of variables that may be set exogenously. CGE modellers often referred to these choices as 'model closure'. Here it is assumed that the government sector always clears its available funds (Eq. 7.41), a fixed value from within these available funds, *GHTRANS*, is transferred to the household sector, and another fixed value is also transferred to savings, *GOVTSAVINGS*. Furthermore, of its available expenditure, the government sector uses a fixed proportion on purchasing each i commodity. These exogenous purchase rates, $GCSP_i$, along with current commodity prices therefore determine the total quantity of each commodity consumed, $govtconsump_i$ (Eq. 7.42).

$$Govtaccount(t+dt) = Govtaccount(t) + (govtincome - govtexpend) \times dt$$
where:
$$Govtaccount(0) = govtexpend(0) \quad (7.36)$$

$$govtincome = factortax + hhldtax + \sum_j prodtax_j \quad (7.37)$$

$$prodtax_j = productionf_j \times pinds_j \times TAXPRODF_j \quad (7.38)$$

$$factortax = \sum_j \sum_h \left(factorsu_{h,j} \times Pfact_{h,j} \times TAXFACT_h \right) \quad (7.39)$$

$$hhldtax = hhldexpend \times TAXHHLD \quad (7.40)$$

$$govtexpend = Govtaccount \quad (7.41)$$

$$govtconsump_i = (govtexpend - GHTRANS - GOVTSAVINGS) \times \frac{GCSP_i}{Pcomd_i} \quad (7.42)$$

Investment and Savings Module

As shown in Figure 7.7, the investment and savings module has a similar structure to the government module. Like the former module, it has a central stock of funds, *Savingsaccount*, which in this case receives additions from savings and subtractions from investment (Eq. 7.43). The value of total savings, *savings*, is calculated from the sum of government savings, *GOVTSAVINGS*, factor income saved, *fincomeinvest*, and household savings, *hhldsavings* (Eq. 7.44). The closure rules applied in the case of the Household sector are relatively straightforward, with total household savings during a period calculated by multiplying the household income during that period, less taxes, by a constant household propensity to save, *SSP* (Eq. 7.45).[145] Similarly, the value of factor income transferred to savings is determined by multiplying factor income, less taxes, by a constant exogenous rate for each factor, $RFISTRANS_h$ (Eq. 7.46). Note that the variables *dispfactincome* and $factorincome_h$ are defined under the households module.

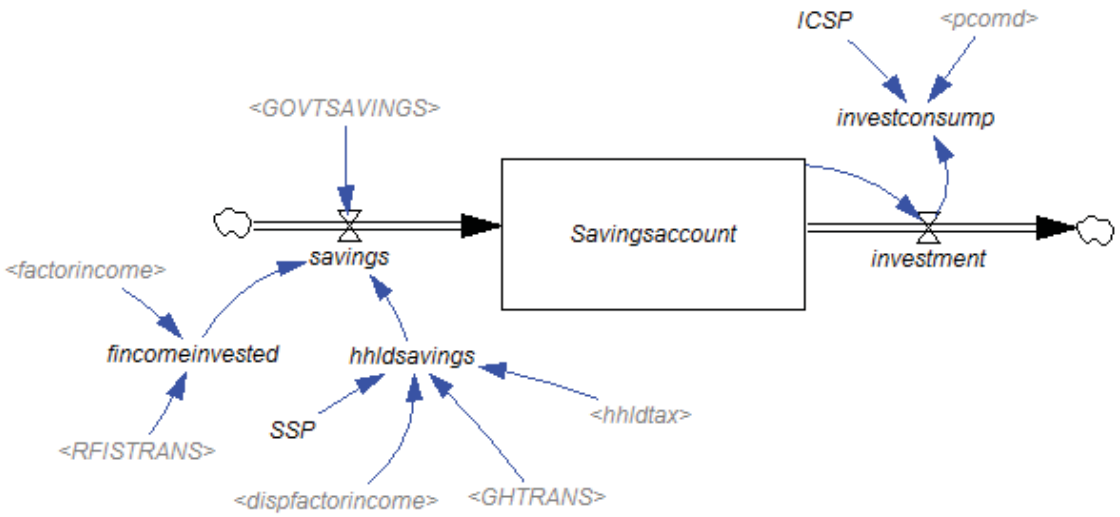

Figure 7.7 Investment and Savings Module Influence Diagram

Notes: *dispfactorincome* = available income from factors, *fincomeinvest* = factor income invested, *GHTRANS* = government to households transfers, *hhldsavings* = household savings, *hhldtax* = household taxes, *ICSP* = investment consumption commodity share, *investconsump* = investment consumption, *pcomd* = commodity demand price, *RFISTRANS* = government to household transfers, *savings* = total savings, *SSP* = household savings share.

Turning now to investment, the total value of investment expenditure during a period is simply set equivalent to *Savingsaccount*, to achieve clearing of the available investment funds (Eq. 7.47). Assuming simply that fixed proportions of investment expenditure are allocated to each

[145] A potential extension to the model could involve the development of an endogenous savings rate where the proportion of income devoted to savings adjusts depending on the returns to savings.

i commodity, $ICSP_i$, and applying current commodity prices, the quantity consumed of each commodity, $investconsump_i$, is calculated as per Eq. 7.48.

$$Savingsaccount(t+dt) = Savingsaccount(t) + (savings - investment) \times dt$$
where: (7.43)
$$Savingsaccount(0) = investment(0)$$

$$savings = hhldsavings + GOVTSAVINGS + fincomeinvested \quad (7.44)$$

$$hhldsavings = (dispfactorincome + GHTRANS - hhldtax) \times SSP \quad (7.45)$$

$$fincomeinvested = \sum_h (factincome_h \times RFISTRANS_h) \quad (7.46)$$

$$investment = Savingsaccount \quad (7.47)$$

$$investconsump_i = investment \times \frac{ICSP_i}{pcomd_i} \quad (7.48)$$

Households Module

The households module provides the final component of the model (Figure 7.8) and again it has a structure similar to the government module.

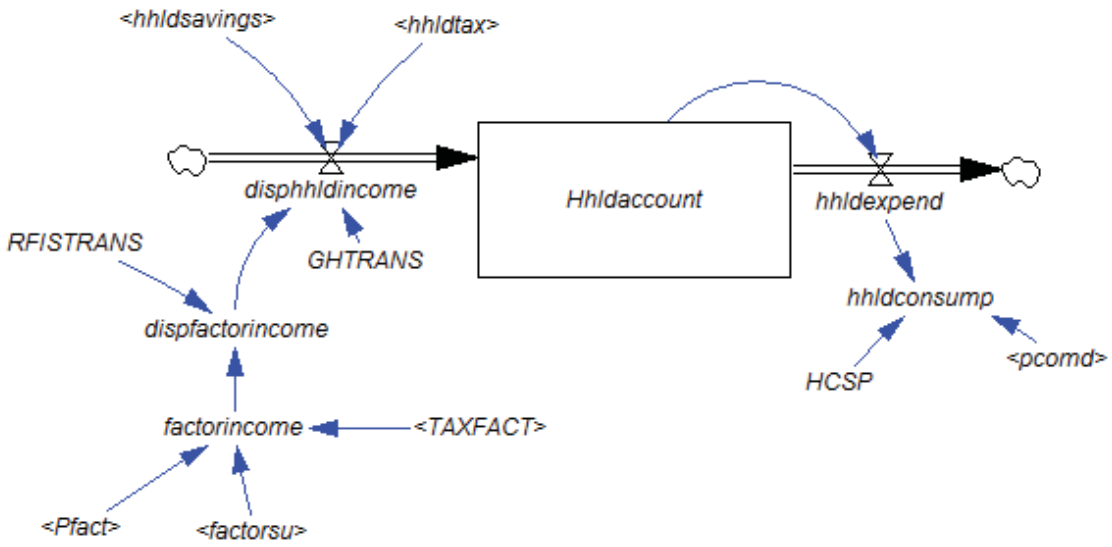

Figure 7.8 Households Module Influence Diagram

Notes: *dispfactorincome* = household income from factors, *disphhldincome* = household disposable income, *factorsu* = factor use, *GHTRANS*= government to households transfers, *HCSP* = household consumption commodity share, *Hhldaccount* = household account, *hhldconsump* = household consumption, *hhldexpend* = household expenditure, *GOVTSAVINGS* = government savings, *hhldexpend* = household expenditure, *hhldsavings* = household savings, *hhldtax* = household taxes, *pcomd* = commodity demand price, *Pfact* = factor price,*RFISTRANS* = share of factor income invested, *TAXFACT* = factor tax rate.

The stock *Hhldaccount* receives household disposable income, *disphhldincome*, and provides expenditure for household consumption, *hhldexpend* (Eqs. 7.49 and 7.50). The value of *disphhldincome* is calculated from the sum available income from factors, *netfactorincome*, and household transfers from government, less household taxes and household income transferred to savings (Eq. 7.51). In turn, *netfactorincome* is defined as the total income from factors (Eq. 7.52) less factor income transferred to savings (Eq. 7.53). Finally, a very simple household consumption function is applied that is analogous to those used in the case of the government and investment and savings modules (Eq. 7.54). The variable $HCSP_i$ defines the exogenous share of household consumption expenditure allocated to commodity i.

$$Hhldaccount(t+dt) = Hhldaccount(t) + (disphhldincome - hhldexpend) \times dt$$
where:
$$Hhldaccount(0) = hhldexpend(0) \quad (7.49)$$

$$hhldexpend = Hhldaccount \quad (7.50)$$

$$disphhldincome = GHTRANS + netfactorincome - hhldsavings - hhldtax \quad (7.51)$$

$$factorincome_h = \sum_j indfactoru_{h,j} \times Pfact_{h,j} \times (1 - TAXFACT_h) \quad (7.52)$$

$$netfactorincome = factorincome_h \times (1 - RFISTRANS_h) \quad (7.53)$$

$$hhldconsumption_i = totalhhldconsumption \times \frac{HCSP_i}{Pcomd_i} \quad (7.54)$$

7.3.2 The Dynamic General Equilibrium-*Seeking* Model with Factor Growth

The primary additional feature in most dynamic CGE models, beyond that of a static CGE, is that key stocks (usually capital and labour) are tracked across time, either through exogenous or endogenous calculations. This enables a series of equilibrium positions to be traced over an impact horizon. In this section, the model developed above is extended to include growth dynamics through labour and capital stock changes. The System Dynamics framework is superior for incorporating such changes, as it allows for the values of capital and labour stocks to be updated continuously, rather than in a step-wise fashion with an assumed equilibrium at the end of each period, as per many recursive dynamic CGE models. Specifically, two additional modules, encompassing labour and capital dynamics, are introduced (Figures 7.9 and 7.10).

Labour Module

Ever since the commentary of Sen (1963), the problem of labour market closure has been a major focus, invoking an extensive controversial theoretical debate in the CGE modelling literature. Typically, a modeller has a choice between (1) assuming that the economy's labour supply is exogenous, and an endogenous wage adjusts until national labour supply and demand are equal, or (2) assuming that the economy-wide wage is exogenous, and an endogenous labour supply adjusts until labour supply and demand are equal. Even with the case-specific adaptions and modifications that can be made to these assumptions, for most real world situations neither approach is entirely satisfactory. As this chapter is concerned with modelling a closed (i.e. global) economy rather than, say, a national economy where there are possible movements of labour in and out of the system, labour is set exogenously. The total stock of labour is thus modelled by applying a set labour growth rate, LGR (Eqs. 7.55 and 7.56), based on projected future population growth with adjustments for changes in age-sex structure. Note, however, that this does not mean the labour is always fully employed. Rather, periods of underutilisation of labour are a characteristic feature of the dynamic adjustment process following introduction of an exogenous shock to the model.

Although labour is in principle a mobile factor of production, with persons able to move between firms and even industries in order to achieve the highest rates of compensation, in practice labour mobility is constrained by the relative supply of, and demand for, particular labour skills. There are a number of possible options for incorporating these dynamics into a model. This chapter disaggregates the available labour force according to a set of identified skills or occupations. The total stock of labour is responsible for 'supplying' to each of the different types of skills, but because of factors such as differences in education and training requirements, there is imperfect substitution (strictly speaking, 'imperfect transformation') in supply. This is represented through a Constant Elasticity of Transformation (CET) function (Eqs. 7.57 and 7.58) where the total supply of labour of skill p, $skills_p$, is determined by the going wage rate for that skill, $Pskill_p$, relative to the economy-wide wage rate, as well as the elasticity of transformation of supply, $ELABTRANS$. The terms $SHAREL_p$ and $SCALEL$ represent CET share coefficients for skill p and the CET scale coefficient, respectively.

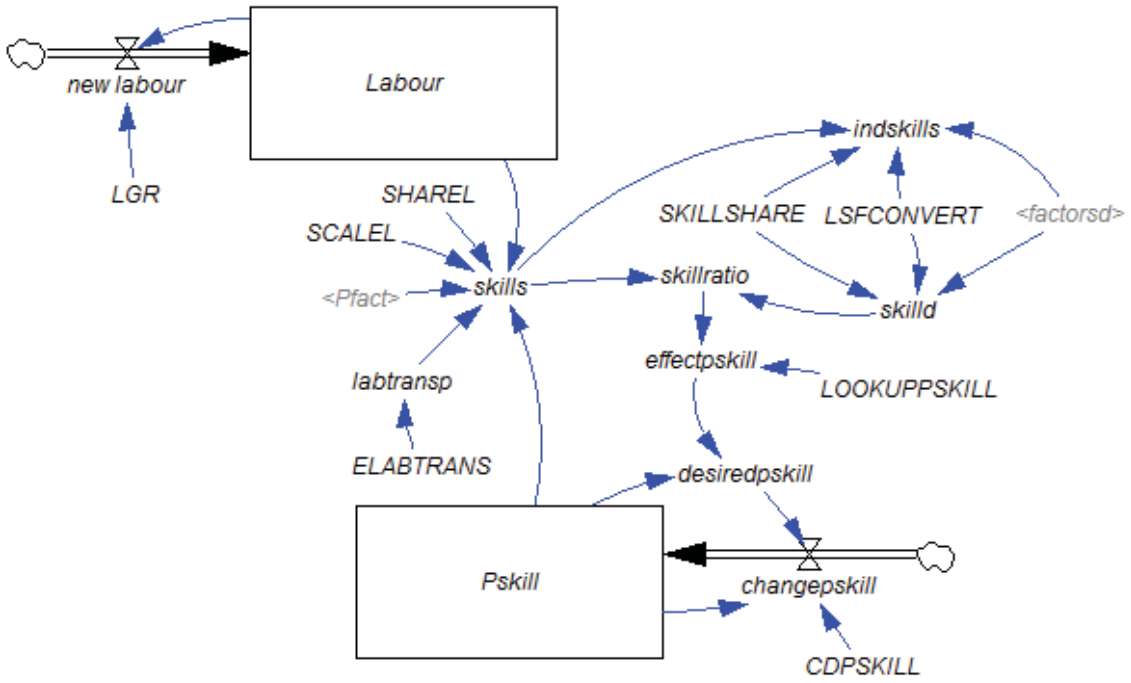

Figure 7.9 Labour Module Influence Diagram

Notes: *CDPSKILL* = change delay for skill price, *changepskill* = increase in skill price, *desiredpskill* = desired skill price, *effectpskill* = skill price change scalar, *ELABTRANS* = elasticity of labour transformation, *factorsd* = factor demand, *indskills* = skill supply to industry, *Labour* = Labour stock, *labtransp* = labour transformation parameter, *LGR* = labour growth rate, *LOOKUPPSKILL* = lookup function for skill price change scalar, *LSFCONVERT* = labour stock to flow converter, *Pfact* = factor price, *Pskill* = skill price, *SCALEL* = scale parameter for labour transformation, *SHAREL* = share parameter for labour transformation, *skilld* = skill demand, *SKILLSHARE* = skill share of total labour.

Having determined the supply of a particular labour skill, the economy-wide price (i.e. wage) for that skill fluctuates depending on relative differences between supply and demand, in much the same manner as other price dynamics in the model (refer to Eqs. F.10–F.14 in Appendix F). The demand for a selected p skill, $skilld_p$, is determined by total labour factor demands by industries (Eq. 7.59), as derived above under the factors module. The fixed coefficient $SKILLSHARE_{p,j}$ defines the amount of labour with skill p required by industry j, relative to total labour demand by industry j. As explained above, it is also necessary to incorporate the scalar, $LSFCONVERT_p$, in order to translate labour as a flow measure from the factors module, into labour as a stock measure for the purposes of this module. Note that it is the $factors_{lab,j}$ converter that constitutes inputs from the factors module into the labour module, and the converter $indskills_{p,j}$, defining the total supply of labour skill p to industry j, that forms inputs from the labour module back into the factors module. This latter converter is calculated by distributing the total supply of each p skill across all j industries, according to each industry's share of the total demand for that skill (Eq. 7.60). Finally, in order to account

for the introduction of labour skills to the model, Eq. 7.32 from the factors module is replaced with Eq. 7.61 below.

$$Labour(t+dt) = Labour(t) + newlabour \times dt$$

where: (7.55)

$Labour(0) =$ size of labour stock at the base year

$$newlabour = Labour \times LGR \tag{7.56}$$

$$skills_p = \left(\frac{SCALEL^{labtransp} \times SHAREL_p \times Pfact_{lab}}{Pskill_p} \right)^{\frac{1}{1-labtransp}} \times Labour \tag{7.57}$$

$$labourtransp_p = \frac{ELABTRANS + 1}{ELABSTRANS} \tag{7.58}$$

$$skilld_p = \frac{\sum_j \left(factorsd_{lab,j} \times SKILLSHARE_{p,j} \right)}{LSFCONVERT_p} \tag{7.59}$$

$$indskills_{p,j} = skills_p \times LSFCONVERT_p \times \frac{factorsd_{lab,j} \times SKILLSHARE_{p,j}}{\sum_j \left(factorsd_{lab,j} \times SKILLSHARE_{p,j} \right)} \tag{7.60}$$

$$factors_{lab,j} = \min \left(\frac{indskills_{1,j}}{SKILLSHARE_{1,j}}, \frac{indskills_{2,j}}{SKILLSHARE_{2,j}}, \frac{indskills_{3,j}}{SKILLSHARE_{3,j}}, \ldots, \frac{indskills_{P,j}}{SKILLSHARE_{P,j}} \right) \times ProdF_{lab} \tag{7.61}$$

Capital Module

While some forms of capital are mobile between industries (e.g. office space, cash funds, human capital), other forms of capital (e.g. machinery, equipment) have very limited mobility. To incorporate these dynamics, the stock of capital held by each industry changes over time through: (1) the addition of new capital occurring either by way of investment or through transfers of mobile capital from other industries, (2) depletion of old capital through depreciation of existing stocks, and (3) loss of mobile capital to other industries (Eq. 7.62).

Depreciation on capital stocks of industry j, $depreciation_j$, is calculated simply by assuming a constant depreciation rate, $RDEP_j$ (Eq. 7.63). Similarly, the quantity of capital held within each industry that is mobile and thus potentially reallocated to other industries, $mcapital_j$, is determined by a constant capital mobility rate $MOBILE_j$ (Eq. 7.64).

In order to remove the effect of commodity price changes in determining the relative quantity of new capital items, the investment undertaken each period is divided by the current capital price, *pcap*, calculated as a weighted average of the prices of individual commodities that make up new capital investment (Eq. 7.65). Having determined the quantity of new capital items, these are distributed amongst industries according to endogenously derived industry shares, $indshareinvest_j$ (Eq. 7.66). An extreme specification of the model would allocate investment to industries according to each industry's share of total capital income. These shares are defined by the variables $capitalincomesh_j$ (Eq. 7.67). Recognising, however, that some investment is mobile across industries, the equation defining $indshareinvest_j$ also includes a set of terms that adjust investment shares to account for differences in capital returns (Eqs. 7.68–7.70). Industries with above-average capital returns receive a larger share of investment funds than their share in capital income, while the converse occurs for industries from which capital returns are below average. Note that the exogenous term *INVESTMOB* represents the proportion of total investment that is mobile between industries.

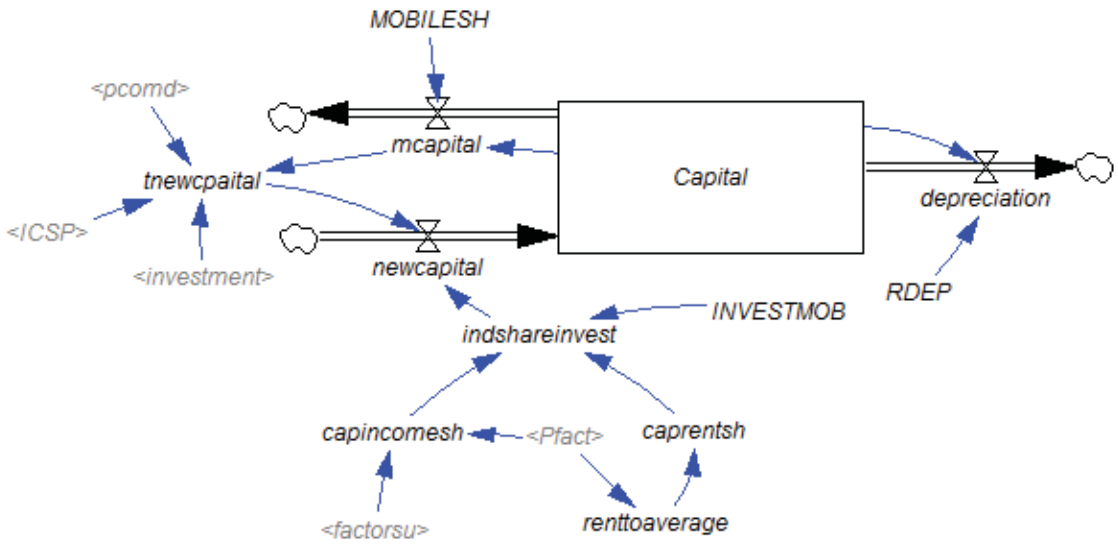

Figure 7.10 Capital Module Influence Diagram

Notes: *capincomesh* = industry share of total capital income, *Capital* = capital stock, *caprentsh* = industry share of investment based on capital returns, *factorsu* = use of factors, *ICSP* = investment consumption commodity share, *indshareinvest* = industry share of total investment, *INVESTMOB* = share of capital income mobile across industries, *mcapital* = quantity of mobile capital, *MOBILESH* = share of capital able to be reallocated, *pcap* = average capital price, *pcomd* = commodity demand price, *Pfact* = factor price, *renttoaverage* = industry rent relative to average rent, *RDEP* = depreciation rate, *tnewcapital* = total new capital.

$$Capital_j(t+dt) = Capital_j(t) + \left(newcapital_j - depreciation_j - mcapital_j\right) \times dt$$

where: (7.62)

$Capital_j(0) =$ size of capital k stock held by industry j at the base year

$$depreciation_j = Capital_j \times RDEP_j \tag{7.63}$$

$$mcapital_j = Capital_j \times MOBILESH_j \tag{7.64}$$

$$totalnewcapital_j = investment \times \sum_i \left(\frac{ICSP_i}{pcomd_i} \right) + \sum_j mcapital \tag{7.65}$$

$$newcapital_j = totalnewcapital \times indshareinvest_j \tag{7.66}$$

$$capincomesh_j = \frac{factorsu_{cap,j} \times Pfact_{cap,j}}{\sum_j factorsu_{cap,j} \times Pfact_{cap,j}} \tag{7.67}$$

$$indshareinvest_j = capincomesh_j \times (1 - INVESTMOB) + caprentsh \times INVESTMOB \tag{7.68}$$

$$caprentsh_j = \frac{renttoaverage_j}{\sum_j renttoaverage_j} \tag{7.69}$$

$$renttoaverage_j = \frac{Pfact_{\text{cap},j}}{\sum_j Pfact_{\text{cap},j}} \tag{7.70}$$

7.4 Behaviour of the Dynamic General Equilibrium-*Seeking* Model

This section illustrates the patterns of behaviour that can be generated by the various models developed above. To facilitate understanding a very simple example is formulated that involves just two economic industries (Ind1, Ind2), each producing one unique type of commodity (Com1, Com2) and utilising two types of labour inputs to production (Skilled, Unskilled). For simplicity it is also assumed that all capital is immobile between industries (for all j, $MOBILESH_j$ = 0), and the possibility of substitution between intermediate goods and factors is ignored.

Two different versions of the model are assessed: (1) the DGES model with constant factors (DGES CF) (as per Section 7.3.1), and (2) the DGES model incorporating factor growth (DGES FG) (as per Section 7.3.2). The initial conditions for both versions of the DGES model are determined from the within economy matrices of the ESAM. The majority of the exogenous constants (e.g. tax rates, government-household transfers) are obtained directly out of this dataset, and are set as constant throughout the study period. Additionally, for demonstration purposes, the elasticities for factor substitution and labour transformation are all arbitrarily set as 2, and then the $SHARE$ and $SCALE$ parameters are determined via a calibration process,[146]

[146] Refer to Hosoe *et al*. (2010) for a step-by-step guide to CGE calibration.

assuming that the DGES models are in equilibrium at the base year. It is also important to note that the exogenous capital depreciation rate, $RDEP$, in both of the DGES models is set so that the quantity of capital depreciated at the base year is equal to the quantity of new capital purchased. This assumption enables us easily to examine the behaviour of the both DGES models in terms of equilibrium growth paths following an exogenous shock.

Results without exogenous shock

The results begin by showing the dynamics of each model with no exogenous changes or shocks introduced. Since each model starts at a position where new industry capital is equal to depreciation, and the labour force and productivity growth rates are set to zero, both models produce a steady state situation where each endogenous variable remains at its base year value (refer to DGES CF and DGES FG results in Figures 7.11 and 7.12). Figures 7.11 and 7.12 also depict the behaviour of the DGES FG model when (1) a population growth rate of 1 percent yr^{-1} is introduced ('DGES FG, 1% pop gr, 0% tech gr'), and (2) a population growth rate of 1 percent yr^{-1} is combined with an increase in the state of technological progress over time ('DGES FG, 1% pop gr, 0.5% tech gr'). This latter adaptation is incorporated by way of a rate of productivity change of 0.5 percent yr^{-1} that augments a firm's capital endowment.

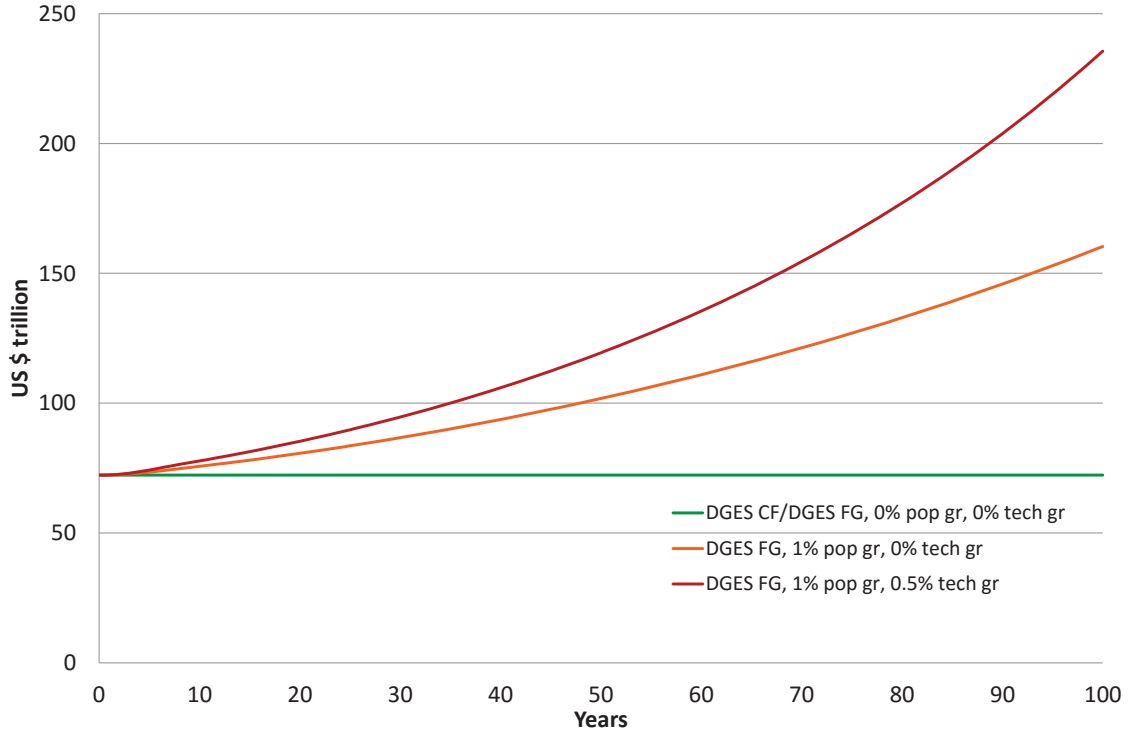

Figure 7.11 Total Economic Output without Economic Shock

Notes: DGES CF= Dynamic General Equilibrium *Seeking* Model with Constant Factors, DGES FG = Dynamic General Equilibrium Model with Factor Growth.

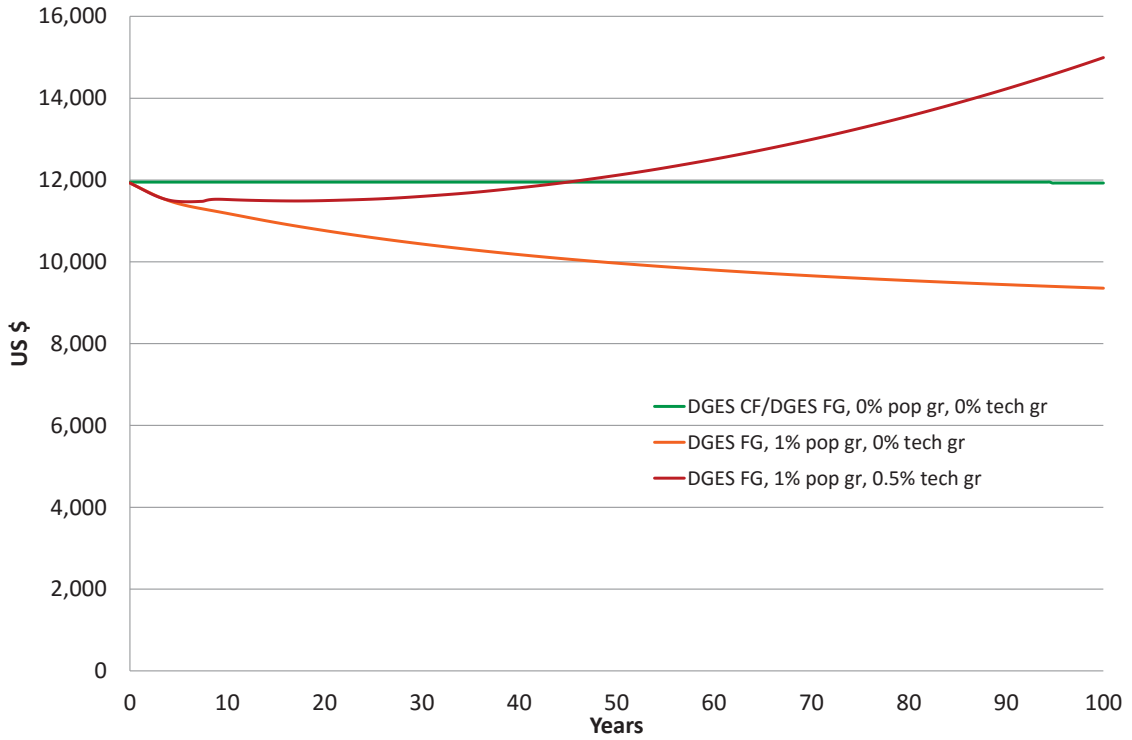

Figure 7.12 Household Consumption per Worker without Exogenous Shock

Notes: DGES CF= Dynamic General Equilibrium *Seeking* Model with Constant Factors, DGES FG = Dynamic General Equilibrium Model with Factor Growth.

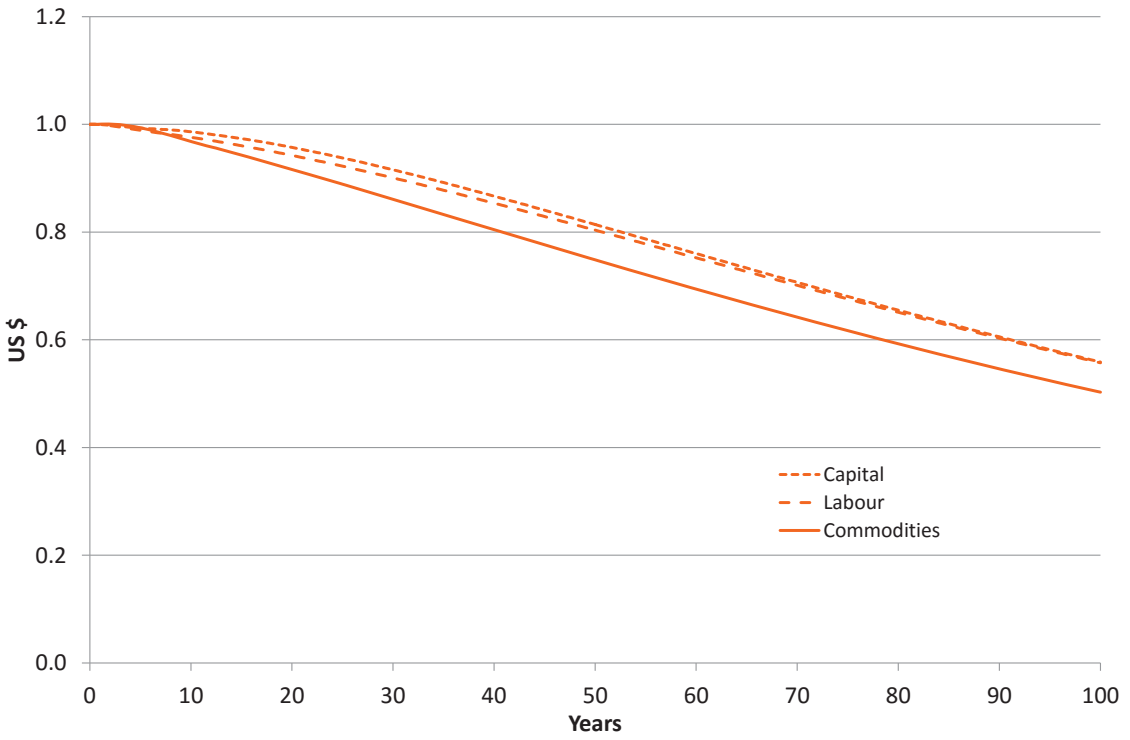

Figure 7.13 **Average Prices for Capital, Labour and Commodities under the Dynamic General Equilibrium-*Seeking* Model with Factor Growth and 1% yr^{-1} Population Growth, Constant Technology and without Exogenous Shock**

When a positive labour-force growth rate is applied in the DGES FG model this continuously drives down the price of labour (Figure 7.13). The price of capital also reduces, although to a lesser extent than the price of labour, because labour-for-capital substitutions reduce the demand pressures on capital. However, following the principle of diminishing marginal productivity, which places limits on how much output can be produced from a set level of capital simply by adding more and more workers, the total rate of economic growth cannot keep pace with the rate of increase in labour. Per capita incomes and expenditures thus start to decline, despite continued absolute increase in economic output. Notice, however, that over time this effect starts to fall away, because the amount of new capital created each period begins to outstrip the amount that is lost through depreciation. Effectively, this is made possible because declining commodity prices enable greater levels of capital to be purchased at lower expense. When the timeframe for analysis is pushed out sufficiently far, the system will eventually reach an equilibrium state where the rate of growth in the capital stock is sufficient to meet the rate of growth in labour. Thus, the amount of commodities consumed per worker becomes constant, and with constant returns to scale in the CES production function, output growth is equivalent to the rate of growth in labour. If we now add the

concept of exogenous productivity or technology change to the model dynamics, the system can actually reach a pathway where the rate of growth in output is above the rate of labour force growth and, hence, the exponential growth in per capita household consumption. Note the consistency of these results with neoclassical growth theory.

Results with exogenous shock

For exposition purposes, reference is again made to a simple example involving just two industries, two commodities, and two labour types. This time, however, the stock of capital held by IND1, which is the smaller of the two industries producing around 10 percent of total economic output, is adjusted down by 50 percent in the initial base year. This may represent a scenario of a natural hazard event, for example, involving widespread damage to buildings, machinery, and other capital held by that industry.

Starting with the DGES CF model, the economy is heavily constrained in the quantity of economic output that can be produced (Figure 7.14). The initial period of impact is characterised by ongoing tightening of these constraints because Ind1 (which produces less output per unit of labour input than Ind2) substitutes labour for lost capital and, hence, demands a greater share of the available labour. Although factor prices rise from the outset due to shortages in supply, the effect on industries is buffered by falling commodity prices, as well as rising household incomes that enable increased household demand for commodities (Figures 7.16 and 7.17). However, within a relatively short time (two years), factor prices reach a point where both industries start to reduce production at quite significant rates. Of course, the falling availability in commodities and thus increasing commodity prices acts to slow-down this trend and then, around Year 4, this leads to industries increasing production again. Over time, this oscillating behaviour is dampened as the model tends towards a new equilibrium state where total output is around 3.8 percent lower than that of the base year situation, and per capita household consumption is around 3.4 percent lower.

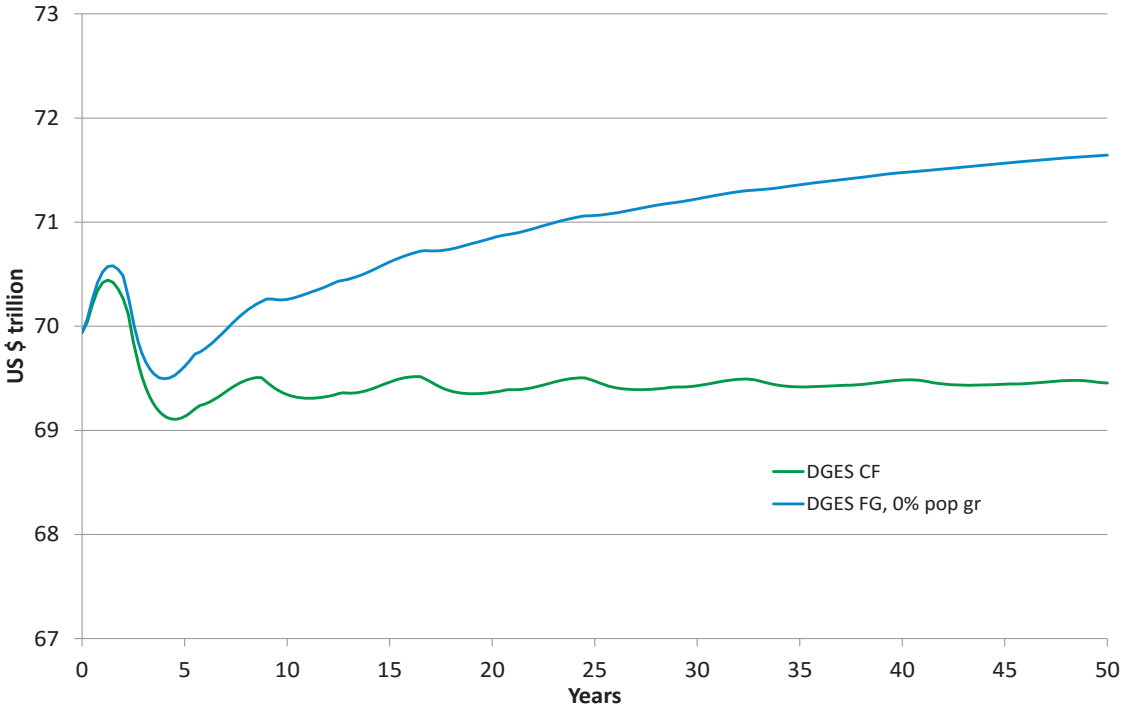

Figure 7.14 Total Economic Output following an Exogenous Shock at the Base Year, Assuming Constant Technology and Population

Notes: DGES CF= Dynamic General Equilibrium *Seeking* Model with Constant Factors, DGES FG = Dynamic General Equilibrium Model with Factor Growth

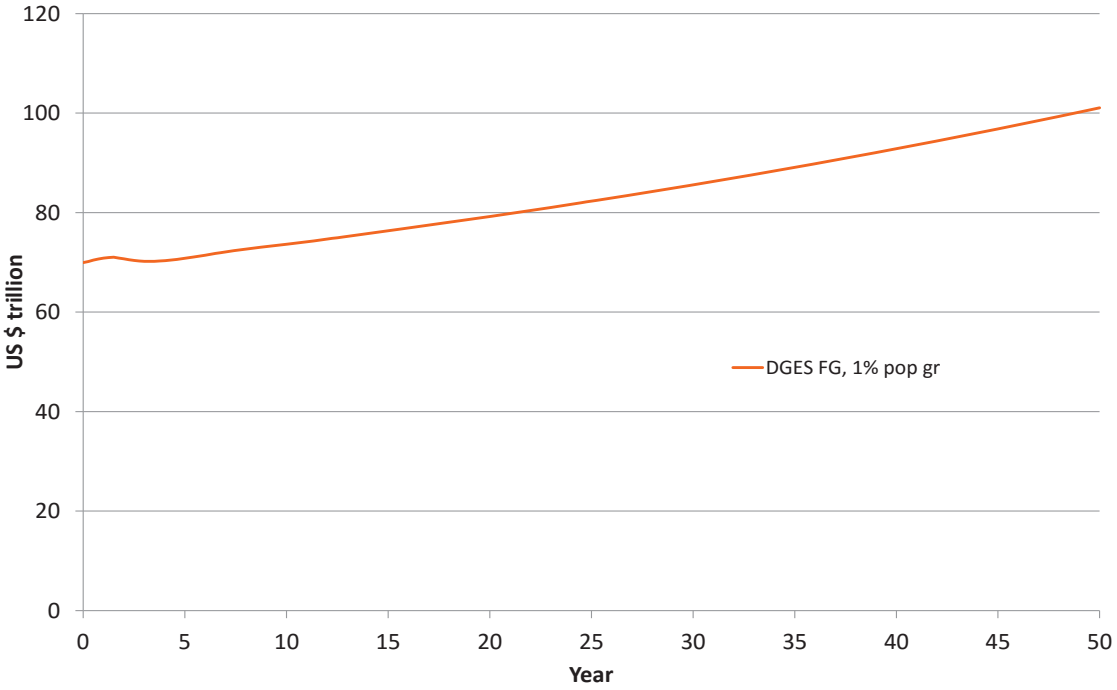

Figure 7.15 Total Economic Output following an Exogenous Shock at the Base Year, Assuming Constant Technology and 1% yr^{-1} Population Growth

Note: DGES FG = Dynamic General Equilibrium Model with Factor Growth.

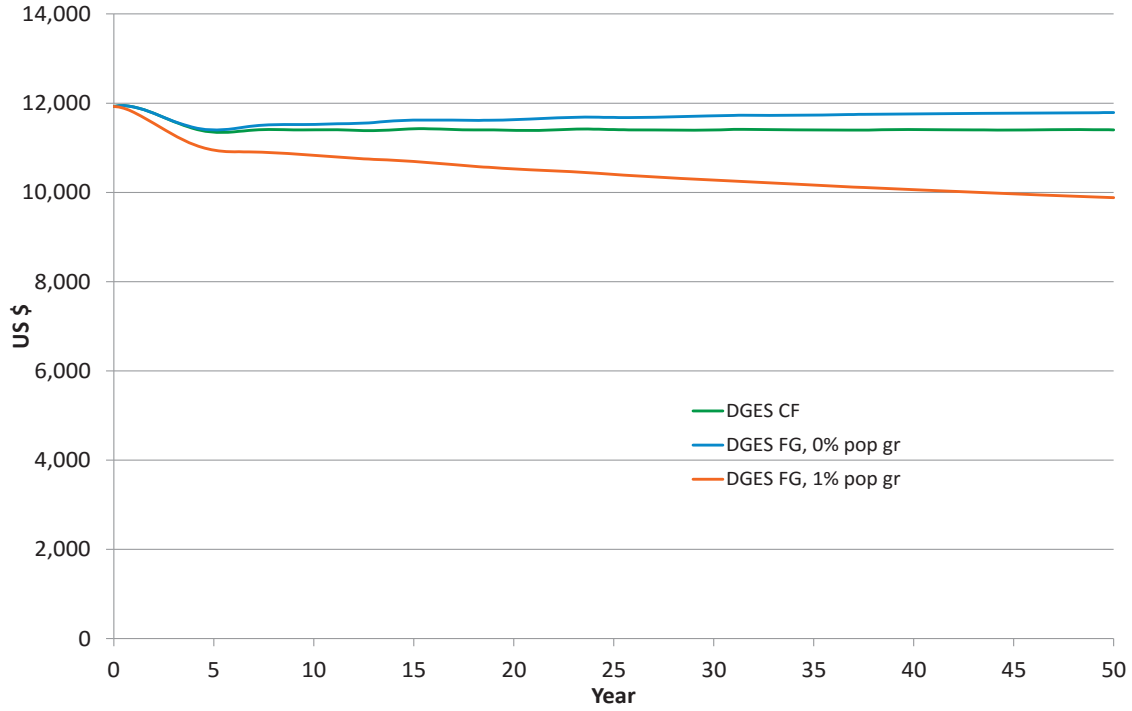

Figure 7.16 **Average Household Consumption per Worker following an Exogenous Shock at the Base Year, Assuming Constant Technology**

Notes: DGES CF= Dynamic General Equilibrium *Seeking* Model with Constant Factors, DGES FG = Dynamic General Equilibrium Model with Factor Growth.

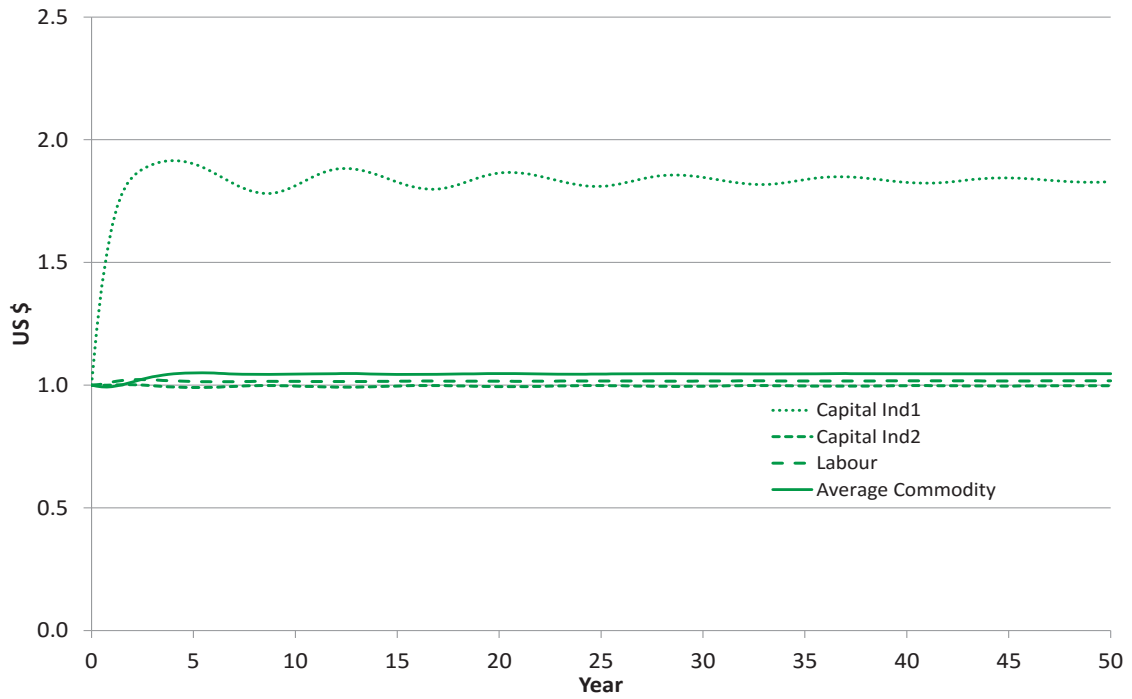

Figure 7.17 **Factor and Commodity Prices in the Dynamic General Equilibrium-*Seeking* Model with Constant Factors following an Exogenous Shock at the Base Year, Assuming Constant Technology**

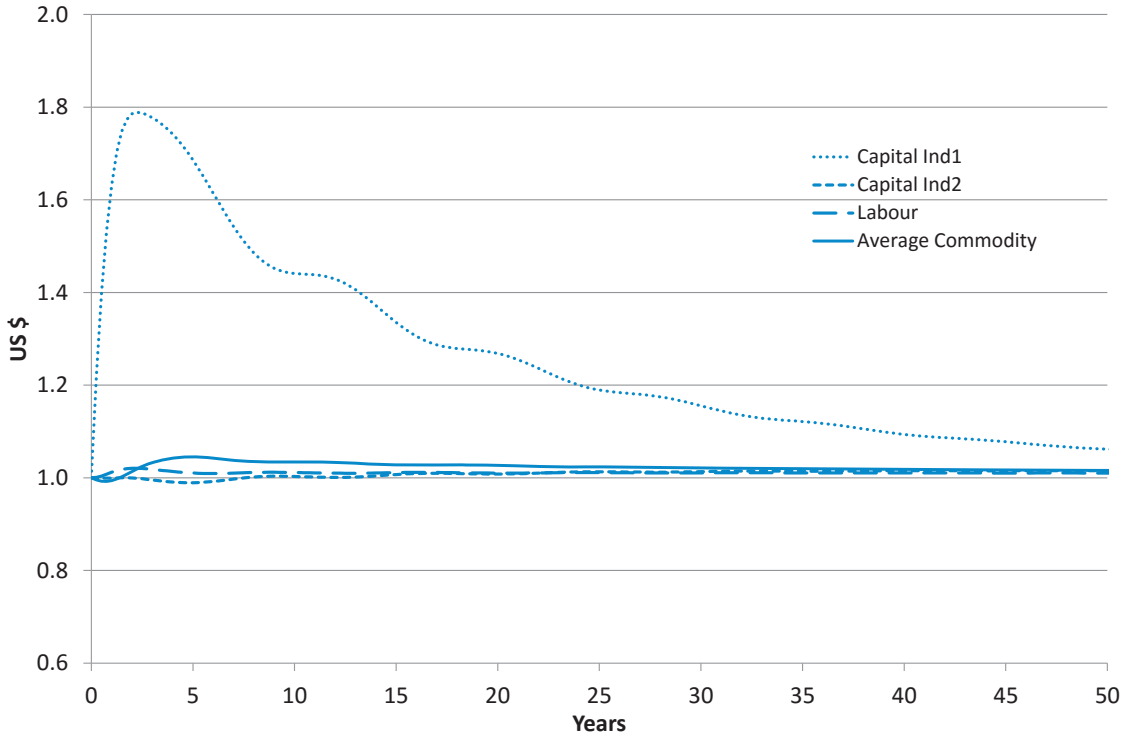

Figure 7.18 **Factor and Commodity Prices in the Dynamic General Equilibrium-*Seeking* Model with Factor Growth following an Exogenous Shock at the Base Year, Assuming Constant Labour and Technology**

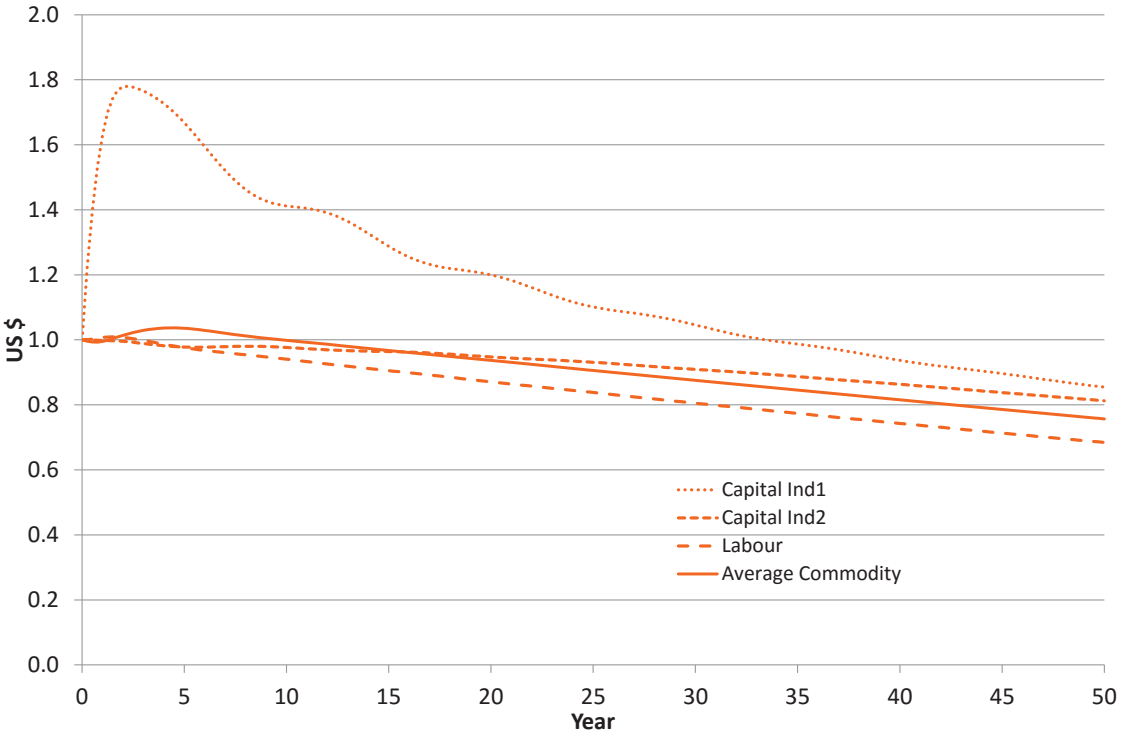

Figure 7.19 **Factor and Commodity Prices in the Dynamic General Equilibrium-*Seeking* Model with Factor Growth following an Exogenous Shock at the Base Year, Assuming 1% yr^{-1} Labour growth and Constant Technology**

To demonstrate the impacts of adding capital accumulation to system behaviours, Figures 7.14, 7.16, and 7.18 show the outputs of the DGES FG model once the capital shock described above is incorporated. So that these results can be easily compared with those of the DGES CF model, the labour force and productivity growth rates are all set to zero for this example. While both models generally exhibit the same oscillatory behaviour following the exogenous shock, the important difference is that the DGES FG model tends towards a new equilibrium that is characterised by higher economic output and consumption levels than that of the DGES CF model. This outcome is understandable when one considers the different treatment of capital between the two models. Under the DGES CF model, there is no process for accounting for capital stock changes, and thus capital lost from the system via the economic shock is lost forever. By comparison, under the DGES FG model, because investment expenditures are fully balanced by the formation of new capital, and new investment is able to concentrate in the industry paying the highest return, over time the initial capital lost from IND1 can be recovered. Eventually, if we push out far enough, the DGES FG model will actually return to the pre-shock equilibrium. This implies that when attempting to evaluate the impacts of some type of economic shock, we should be concentrating particularly on the pathway for adjustment that the system may follow, and the length of time over which this may occur (as per the approach outlined in this chapter), rather than the actual 'new equilibrium' position (as per standard CGE models).

Following on from this last point, Figures 7.15, 7.16, and 7.19 respectively show the effect on economic output, average consumption per worker, and prices when the economic shock is applied in the context of ongoing labour force growth of 1 percent yr^{-1}. Note that these results for total economic output are presented in a separate graph from the previous examples, due to scale differences. Once again the system behaves in an oscillatory fashion following the exogenous shock; however, this time it occurs against the background of increasing labour availability, but diminishing marginal productivity. Within a relatively short time the system returns to the same equilibrium growth path that characterised the pre-shock version of the model.

7.5 Concluding Comments

The introduction section of this chapter identified that an important contribution made by the DGES model is the explicit consideration of time path trajectories. Related to this, an advantage of the System Dynamics approach, compared with optimisation/mathematical

programming models, is an ability to more conveniently interface to models of other systems, including stock-flow models as typically employed for environmental systems. To complete this chapter, it is also worth discussing, briefly, the pedagogic nature of the DGES model, which has particular relevance to the sustainability-related objectives of this thesis.

As explained in Chapters 1 and 2, a key objective in constructing, testing, and running models is to foster understanding of systems, including the processes, interactions and feedback mechanisms that generate dynamics and structure. Models are a type of 'learning tool' that assist us in building intuition of system behaviour, and increase our ability to envisage and select resilient-building strategies. Although CGE modelling has become a standard tool for investigating the behaviour of economic systems, the models are typically very complex to implement and thus usually interrogated only by a relatively small community of global 'experts'.[147] This means that for most people, there is little opportunity to experiment with practical applications of general equilibrium theory and develop improved understanding of CGE as a decision-support tool. Such a 'black box' approach to modelling may cause few problems for problems, such as in many industrial or engineering applications, where the nature of the system is already well understood. However, in the case of socio-economic models, the assumptions are often quite controversial or questionable, and the opaqueness of such models masks important assumptions and discourages criticism.

The DGES model put forward in this chapter demonstrates an alternative approach to organising and communicating ideas and hypotheses around general equilibrium theory which would appear, for most audiences, to be more intuitive and easy to understand. In particular, the time path trajectories produced by the System Dynamics approach more easily enables users to envisage the interplay of causes and feedback structures underpinning model outcomes.[148] Any erratic or unstable behaviour is obvious, and will quickly force model users

[147] CGE models are usually framed as an optimisation or mathematical programming problem built within specialised mathematical packages, e.g. GAMS (General Algebraic Modelling System), containing specific optimization 'solver' modules. Such packages have steep learning curves and require understanding of specialist programming languages. Even at universities CGE models are rarely taken into the classroom, especially at the undergraduate level, due to perceived deficiencies by most students in the necessary programming skills for their operation. Instead, the teaching of equilibrium theory tends to be more of an abstract approach, centred on difficult mathematical equations and reasoning (e.g. Peng (2009)).

[148] The systems dynamics approach is also supported by a number of software modelling tools, the most notable being Stella, Vensim, Powersim, Madonna, ModelMaker4, and Simile. These software resources greatly simply the process of model development and iteration, to the extent that programming is no longer needed to put together models, and only very basic numeric and mathematical skills are

to re-evaluate core assumptions. It is recognised that some components of the DGES model are relatively unsophisticated compared with other economic models. For example, in the household consumption function there is no distinction between commodities necessary to satisfy basic needs and more luxury items. In addition, factors that may cause change in the rate of savings are not considered, and the global nature of the model does not lend to the consideration of trade flows. Nevertheless, for many purposes the model will be sufficient, or in any case it provides the 'basic building blocks' that can be further refined for future simulations as appropriate.

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required. Graphical interfaces also enable model alterations to by readily made and analysed within minutes.

Chapter 8

A Dynamic Biogeochemical Cycling Model of the Global Environment

8.1 Introduction

In this chapter, a System Dynamics model of the global biogeochemical cycles is developed; known as the Dynamic Global Biogeochemical Cycling Model (DGBCM). Based on the earlier modelling work of McDonald (2005), the DGBCM brings together the static biogeochemical cycling databases developed in Chapters 4 and 5, with environmental commodity stock data presented in Appendix E, to develop a highly integrated model of the Earth's biogeochemical cycles. As per McDonald's (2005) model, the key strength of the DGBCM lies in the high degree of coupling that exists between the C, N, P and S cycles.

The structure of this chapter is as follows. Section 8.2 provides a brief overview of recent attempts to model the biogeochemical cycles in an integrated manner. Section 8.3 then provides a full description of the DGBCM, including all environment commodity stocks and flows,[149] flow equations and parameters, while Section 8.4 demonstrates the behaviour of the DGBCM using a steady state analysis with supporting commentary. Finally, Section 8.5 concludes by identifying the key limitations of the DGBCM and possible areas for further research. The DGBCM is presented as a System Dynamics model, developed in the Vensim DSS® software package, in the Chapter 8 directory of the accompanying CD-ROM. The program code for the model, DBGCM.txt, is also contained within this directory.

8.2 Dynamic Modelling of the Global Biogeochemical Cycles

The majority of global biogeochemical models, both static and dynamic, have focused on developing descriptions of the dynamics of a particular cycle (see, for example, Bolin *et al*. (1979), Bowen (1979), Schlesinger (1991, 1997), Butcher *et al*. (1992), Charlson *et al*. (1992), Jahnke (1992), Smil (2000), Brimblecombe (2005), Galloway (2005), Ruttenberg (2005), Filippelli (2008)). Although the modelling of coupled biogeochemical cycles at the scale of

[149] Note that a flow is defined as any transfer of mass into or out of a stock. More than one flow may occur for any given process. In addition, given the adherence to mass balance, any mass flow out of a stock must be balanced by an equal mass flow into another stock.

individual ecosystems has received increasing attention over recent years, the analysis of coupled biogeochemical cycles across ecosystem boundaries is identified as a critical area for ongoing research (Finzi *et al*. 2011). Only a handful of global models exist that capture the dynamic interdependencies that exist between the Earth's biogeochemical cycles. In the words of den Elzen *et al*. (1997, p.161), "Research has hitherto mainly been focused on the separate global cycles rather than on interactions between the various global cycles … What is lacking so far, however, is an integrated modelling framework which describe the global cycles of carbon, nitrogen, phosphorus and sulphur". McDonald (2005, p.481) furthers this argument by stating that the C, N, P, and S[150] biogeochemical cycles are characterised by "inextricably interconnected feedbacks form[ing] an organised whole, a complex system, the properties of which are more than the sum of its component parts". The remainder of this section is devoted to a brief review of the dynamic biogeochemical cycling models that consider connectivity between the cycles.

8.2.1 Mackenzie Model

This box model, developed by Mackenzie *et al*. (1993), focuses on the dynamics of the C, N, and P biogeochemical cycles within the natural world, with no reference to human socio-economic systems. The most significant contribution of the Mackenzie model is its attempt to model the element cycles in an integrated manner, as opposed to the common approach of studying the cycles in isolation. On close of inspection of the Mackenzie *et al*. (1993) model, however, it is noted that contrary to its description, the number of feedbacks between the cycles are relatively few. The principal points of connection occur simply in relation to biological matter, where the model builders rely on the supposition that matter is comprised of a common ratio of C:N:P (refer to Redfield *et al*. (1963) and Atkinson and Smith (1983)). It assumed that P is the limiting element in regards to the formation of biological matter, thus controlling the flow and stock values for the other two elements. Flows are modelled using first order rate equations.[151]

[150] He also modelled the dynamics of the hydrogen cycle.
[151] Refer to Section 8.3.3.

8.2.2 Tool to Assess Regional and Global Environmental and Health Targets for Sustainability

The TARGETS (Tool to Assess Regional and Global Environmental and health Targets) model (Rotman *et al*., 1994; Rotman and de Vries, 1997) is another global integrated assessment model. It includes five sub-models, one of which simulates biogeochemical cycles (C, N, P, and S) as well as climate change dynamics. Den Elzen *et al*. (1997) created the biogeochemical cycling sub-model, known as Cycles. The Cycles sub-model captures the entire effect chains of C, N, P and S and their interconnections using a simple box model representing the physical, chemical and biological fluxes between the atmosphere, hydrosphere, and terrestrial biosphere (den Elzen *et al*., 1995; 1997). Cycles considers the future fate of anthropogenic emissions of C and N compounds given the constraint that the budgets are balanced. Simulation runs using the Cycles sub-model show that incorporating terrestrial C feedbacks (i.e. CO_2 fertilisation and temperature feedbacks) is not enough to create a balanced C budget. If, however, N fertilisation via anthropogenic N depositions on temperate forests is included, then C budgets may be balanced. In this way, Cycles emphasised the need to consider the global biogeochemical cycles as a whole, rather than in separation.

8.2.3 Global Unified Meta-model of the Biosphere

The GUMBO (Global Unified Model of the BiOsphere) model (Boumans *et al*., 2002) is a Stella® System Dynamics model. The particular objective of GUMBO is to model the complex, dynamic inter-linkages between social, economic and biophysical systems on a global scale, focusing on ecosystem goods and services and their contribution to sustaining human welfare. While GUMBO's creators were not concerned specifically with biogeochemical cycles, the model's objective has led to the inclusion of modules dealing specifically with the C and N cycles, although with relatively few stocks and processes. GUMBO deals with a great range of other components of the Earth system, including the hydrological cycle, environmental flows of silicate minerals, economic production, welfare, and the provision of ecosystem goods and services. GUMBO is a spatially explicit model with stocks and flows covering 11 biomes or ecosystem types.

8.2.4 Integrated Modelling of Global Environmental Change

The Netherlands Environmental Assessment Agency (MNP)[151a] (Bouwman *et al*., 2006) created the IMAGE (Integrated Model to Assess the Global Environment) 2.4 model. It represents the culmination of many years of development beginning in the 1980s by the Netherlands' National Institute for Public Health and the Environment, and, since 2006, by the Netherlands Environmental Assessment Agency. IMAGE has been used in several international assessments including the IPCC's Special Report on Emission Scenarios (Nakicenovic *et al*., 2000), the Third Global Environment Outlook (United Nations Environment Programme, 2002), the Millennium Ecosystem Assessment (Raskin, 2005), and the Global Biodiversity Outlook (Secretariat of the Convention on Biological Diversity, 2010). It represents one of the leading frameworks for integrated assessment of global sustainability issues.

IMAGE 2.4 is an integrated spatially explicitly and dynamic modelling framework which covers in socio-economic terms 26 regions, with climate, land cover and land-use change represented at a 0.5 x 0.5 degree grid scale across the globe. It provides a comprehensive coverage of the direct and indirect pressures on human and natural systems closely related to human systems (Bouwman *et al*., 2006). In terms of biogeochemical cycling, the latest documentation on the IMAGE model includes chapters on the C and N nutrient cycles. The C cycle model accounts for important feedbacks relating to changing climate, CO_2 concentrations and land use. It also enables evaluation of the potential for C sequestration by natural and planted vegetation. The N cycle model focuses on the major N surface-nutrient flows, and their balances, along with reactive N emissions from point and non-point sources. Coupling between the cycles is through atmosphere-ocean, and atmosphere-terrestrial biosphere exchanges.

8.2.5 Global Biogeochemical Cycling Model

The GBCM (Global Biogeochemical Cycling Model; McDonald, 2005) is a Vensim® System Dynamics box-model constructed as part of a PhD thesis. The strength of the GBCM rests in its extensive coupling of the element cycles. It considers not only major element flows, but also sizeable secondary reactants or by-products associated with these flows. The GBCM goes beyond the Mackenzie model by creating a very high level of integration across the biogeochemical cycles, thus enabling consideration of complex feedbacks and interrelationships. It provides full stoichiometric mass-balance equations, based on the work of Patterson (2002), for 73 biogeochemical processes, tracing the flow of C, N, P, S and

hydrogen elements between 21 environmental stocks. McDonald (2005) argues that the biogeochemical cycles are inextricably interconnected through complex feedbacks and, thus, any study of the human impacts on the cycles requires an integrated assessment approach. Using the GBCM, he demonstrates that the seemingly benign human perturbation of a biogeochemical process in one element cycle may through feedback loops result in considerable unforeseen impacts in other cycles.

McDonald (2005) relies solely on first order rate constants, with the rate of each biogeochemical process defined as proportional to the magnitude of a selected donor stock in that process. While this type of equation appears to be a common tool used in ecological modelling, and is likely to be valid for many of the biogeochemical processes, it is also possible that for some processes other relationships will be more appropriate. Sarmiento and Gruber (2006), for example, model the rate at which CO_2 is taken up by the oceans as dependant, not only on the concentration of CO_2 in the atmosphere donor stock, but also on the concentration of dissolved CO_2 in the receiving oceanic stock. Note that since the GBCM does not include anthropogenic processes, some of the most important influences on the biogeochemical cycles, such as CO_2 emissions from fossil fuel combustion, are absent.

8.2.6 A Note on Climate Models

The concentrations of C, N and S gases and aerosols within the atmosphere are very important in determining climatic conditions. Given the strong level of importance presently placed on climate change research within the world's scientific community, a significant proportion of the current research on biogeochemical cycles relates to the assessment of feedbacks between these cycles and climate. Early models for climate assessment generally utilised an 'offline' C cycle model to generate estimates of atmospheric C under a given anthropogenic emission scenario and, in turn, the atmospheric C trajectory is used to drive an ocean-atmospheric general circulation model to calculate global climate change (Friedlingstein *et al*., 2006). Over recent years, however, the need to incorporate feedbacks between global climate and the operation of the C and other nutrient cycles, has received much recognition (Friedlingstein *et al.,* 2006; Hibbard, *et al*., 2007). The specific processes highlighted for further research include nutrient limitations on primary production, fire, succession, changes in vegetation patterns, ocean bottom chemistry and tropospheric ozone dynamics. Although many of the current generation of climate models, as utilised within the fifth phase of the Climate Model Intercomparison Project (Taylor *et al*. 2012), include an interactive C cycle

model and sometimes models of other biogeochemical cycles, many of these processes are still not yet fully represented (Ciais, 2013). The modelling of climate-biogeochemical cycle feedbacks is thus an area of current research.

8.3 The Dynamic Global Biogeochemical Cycling Model

The Dynamic Global Biogeochemical Cycling Model (DGBCM), as developed in this thesis, adopts a systems approach as its guiding principle, the objective of which is not to study the element 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 occur in several spheres, namely: the atmosphere, terrestrial biosphere, oceans, and lithosphere. The DGBCM captures dynamics in the DGBCM using a quasi-steady state[152] box model consisting of a system of environmental commodity stocks (reservoirs) and biogeochemical process that cause flows into and out of the commodity stocks.

8.3.1 Environmental Commodity Stocks

The DGBCM consists of a number of reservoirs covering the atmosphere, terrestrial biosphere, oceans and lithosphere. Specifically, it has 12 C stocks, 11 N stocks, 8 P stocks, and 10 S stocks (see Table 8.1). The acute reader will have already noticed that these stocks are aggregated when compared with those discussed in Chapter 5. The key reason for aggregation is to keep the dynamic modelling of the biogeochemical cycles tractable. Appendix E, Table E.5, provides a concordance mapping the Chapter 5 stocks to the stock definitions used in this chapter.

[152] Properties of a steady state system remain constant over time. The DGBCM is constructed so that stocks and flows will tend towards such a steady state. However, as the system is not at a steady state to begin with, many environmental stocks are very slow to change, and as the model does not include relatively significant environment-economy flows occurring at the base year, the transition to a steady state is anticipated to be of long duration.

Table 8.1 C, N, P, and S Stocks included in the Dynamic Global Biogeochemical Cycling Model

	Elemental Cycle			
Sphere	Carbon	Nitrogen	Phosphorus	Sulphur
Atmosphere	*AtmosnecC*	*AtmosnecN* *Atmosn2N*		*AtmosnecS*
Terrestrial biosphere	*VegezoomasC*	*VegezoomasN*	*VegezoomasP*	*VegezoomasS*
	DetritusC	*DetritusN*	*DetritusP*	*DetritusS*
	SoilC	*SoilN*	*SoilP*	*SoilS*
Marine biosphere	*OceanpandcC*	*OceanpandcN*	*OceanpandcP*	*OceanpandcS*
	OceanhumusC	*OceanhumusN*	*OceanhumusP*	*OceanhumusS*
	OceannecC	*OceannecN*	*OceannecP*	*OceannecS*
	OceancalccarbC			
Lithosphere	*CoalC*	*CoalN*	*CoalP*	*CoalS*
	GasC			
	LithosphereC	*LithosphereN*	*LithosphereP*	*LithosphereS*
	PetroleumC	*PetroleumN*		*PetroleumS*

The *AtmosnecC*, *AtmosnecN* and *AtmosnecS* environmental stocks encompass all key atmospheric compounds containing respectively C, N and S, but exclude atmospheric N_2, which has its own stock, *Atmosn2N*. The terrestrial biosphere is made up of three distinct stocks: *Vegezoomas*[153] (i.e. primary producers (terrestrial vegetation), and secondary/heterotrophic organisms including zoomass (animals), excluding prokaryotes); *Detritus*[154] (i.e. fresh inputs of organic matter in and on the upper layers of the soil profile including leaf litter, dung, moulted materials and corpses); and *Soil*[155] (i.e. all inorganic and organic forms contained in soils, including prokaryotes[156] and fungi). A further four stocks account for C, N, P, and S in the oceans: *Oceanpandc*[157] (i.e. oceanic producers and consumers); *Oceanhumus*[158] (i.e. an aggregate stock of particulate and dissolved organic matter derived from river discharge, dead and decaying organisms, partial remineralisation of sediment, phytoplankton extracellular release, and decomposer organisms); *Oceannec*[159] (i.e. ocean inorganic forms of each element); and in the case of the C cycle only, *Oceancalccarb* (i.e. precipitated $CaCO_3$ from skeletal and protective tissues). Finally, there are four lithosphere stocks covering, to varying

[153] Named *VegezoomasC*, *VegezoomasN*, *VegezoomasP* and *VegezoomasS* respectively for the C, N, P, and S cycles.
[154] Named *DetritusC*, *DetritusN*, *DetritusP* and *DetritusS* respectively for the C, N, P, and S cycles.
[155] Named *SoilC*, *SoilN*, *SoilP* and *SoilS* respectively for the C, N, P, and S cycles.
[156] These account for the vast majority of heterotrophic biomass on Earth.
[157] Named *OceanpandcC*, *OceanpandcN*, *OceanpandcP* and *OceanpandcS* respectively for the C, N, P, and S cycles.
[158] Named *OceanhumusC*, *OceanhumusN*, *OceanhumusP* and *OceanhumusS* respectively for the C, N, P, and S cycles.
[159] Named *OceannecC*, *OceannecN*, *OceannecP* and *OceannecS* respectively for the C, N, P, and S cycles.

degrees, the C, N, P, and S cycles – *Coal*,[160] *GasC* (i.e. natural gas), *Petroleum*,[161] and *Lithosphere*[162] (i.e. covering all remaining organic and inorganic C, N, P and S located in the lithosphere).

To enable ease of understanding, and to also avoid unnecessary repetition of equations, generic stock names (e.g. $Envstock_m{}^C$, $Envstock_m{}^N$) are used in the remainder of this chapter to define process flows and converters. Keeping with the framework laid out in Figure 3.4 in Chapter 3, the subscript *m* denotes a particular environmental commodity, while C, N, P or S superscript denotes the element cycle that the commodity belongs too.

8.3.2 Environmental Commodity Flows

Stocks of C, N, P, and S environmental commodities connect to each other by way of 147 flows representing 79 biogeochemical processes. Note that the number of flows exceeds the number of processes, as more than one flow may exist between different stocks for a given process. Table 8.2 provides a summary of these flows. Column 1 of Table 8.2 labelled 'Process code' provides a short name for the biogeochemical process included in the model, while Column 2 'Process name' provides a full description of the process. Columns 3, 4, and 5 describe the biogeochemical processes noted in Columns 1 and 2 in flow terms. Note that the last letter of the Column 3 'Flow code' denotes to which cycle the flow belongs. Using the biogeochemical process 'vegetation wildfires' (Column 2) as an example, we can see that it has the process code, *wfve* (Column 1). Associated with the *wfve* process are 3 C cycle flows: *wfve1C* (Column 3) that records release of emissions/particulates into the *AtmosnecC* stock (Column 5) from the burning of the material contained in the *VegezoomasC* stock (Column 4); *wfve2C* that records a flow between *VegezoomasC* and *DetritusC*; and *wfve3C* between *VegezoomasC* and *LithosphereC*. The *wfve* process also has 3 N cycle flows (i.e. *wfve1N*, *wfve2N*, and *wfve3N*), 1 P cycle flow (i.e. *wfve1P*) and 2 S cycle flows (i.e. *wfve1S* and *wfve2S*).

Once again, the acute reader will have noticed that the number of biogeochemical processes included in the DGBCM is less than in Chapter 5. This was necessary to keep the thesis tractable. Table D.5 within Appendix D provides a concordance mapping the Chapter 5 biogeochemical processes to the processes applied in this chapter.

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[160] Named *CoalC*, *CoalN*, *CoalP* and *CoalS* respectively for the C, N, P, and S cycles.
[161] Named *PetroleumC*, *PetroleumN* and *PetroleumS* respectively for the C, N, and S cycles.
[162] Named *LithosphereC*, *LithosphereN*, *LithosphereP* and *LithosphereS* respectively for the C, N, P, and S cycles.

Table 8.2 Biogeochemical Processes and Flows included in the Dynamic Global Biogeochemical Cycling Model

Process code	Process name	Flow code	From Stock	To Stock
afix	N_2 fixation by lightning	*afix1N*	*fromAtmosnecN*	*toAtmosn2N*
arnl	Stratospheric destruction of N_2O	*arnl1N*	*fromAtmosn2N*	*toAtmosnecN*
cdrl	Release of CO_2 from the oceans	*cdrl1C*	*fromOceannecC*	*toAtmosnecC*
cdup	Uptake of CO_2 by the oceans	*cdup1C*	*fromAtmosnecC*	*toOceannecC*
cexc	C extracelluar release	*cexc1C*	*fromOceanpandcC*	*toOceanhumusC*
		cexc2C	*fromOceanpandcC*	*toAtmosnecC*
cexp	Export of C to the oceans	*cexp1C*	*fromSoilC*	*toOceanhumusC*
		cexp2C	*fromSoilC*	*toOceannecC*
		cexp3C	*fromSoilC*	*toOceancalccarbC*
cibr	Deep burial of $CaCO_3$ sediments	*cibr1C*	*fromOceancalccarb*	*toLithosphereC*
cobr	Deep burial of organic C sediments	*cobr1C*	*fromOceanhumusC*	*toLithosphereC*
como	C mortality of marine prdcrs & cnsmrs	*como1C*	*fromOceanpandcC*	*toOceanhumusC*
corg	Organic matter C processing	*corg1C*	*fromOceanhumusC*	*toOceannecC*
		corg2C	*fromOceanhumusC*	*toAtmosnecC*
crot	C litter decomposition	*crot1C*	*fromDetritusC*	*toSoilC*
csol	Other C soil processing	*csol1C*	*fromSoilC*	*toAtmosnecC*
ctmo	C terrestrial litterfall & mortality	*ctmo1C*	*fromVegezoomasC*	*toDetritusC*
ctse	Sedimentation of organic C in soils	*ctse1C*	*fromSoilC*	*toLithosphereC*
cwet	Weathering of C crustal rocks	*cwet1C*	*fromLithosphereC*	*toSoilC*
		cwet2C	*fromAtmosnecC*	*toSoilC*
cwfs	C soil wildfires	*cwfs1C*	*fromSoilC*	*toAtmosnecC*
		cwfs2C	*fromSoilC*	*toDetritusC*
		cwfs3C	*fromSoilC*	*toLithosphereC*
czpr	C other zoomass processes	*czpr1C*	*fromVegezoomasC*	*toAtmosnecC*
fffm	Geological transformation of kerogen	*fffm1C*	*fromLithosphereC*	*toGasC*
		fffm1N	*fromLithosphereN*	*toCoalN*
		fffm1P	*fromLithosphereP*	*toCoalP*
		fffm1S	*fromLithosphereS*	*toCoalS*
		fffm2C	*fromLithosphereC*	*toPetroleumC*
		fffm2N	*fromLithosphereN*	*toPetroleumN*
		fffm2S	*fromLithosphereS*	*toPetroleumS*
		fffm3C	*fromLithosphereC*	*toCoalC*
gecd	Geological emissions of CO_2	*gecd1C*	*fromLithosphereC*	*toAtmosnecC*
geme	Geological emissions of CH_4	*geme1C*	*fromGasC*	*toAtmosnecC*
gesg	Geological emissions of S gases	*gesg1C*	*fromLithosphereC*	*toAtmosnecC*
		gesg1S	*fromLithosphereS*	*toAtmosnecS*
hdcc	Hydrothermal inputs of $CaCO_3$	*hdcc1C*	*fromLithosphereC*	*toOceancalccarbC*
losc	Coal loss	*losc1C*	*fromCoalC*	*toLithosphereC*
		losc1N	*fromCoalN*	*toLithosphereN*
		losc1P	*fromCoalP*	*toLithosphereP*
		losc1S	*fromCoalS*	*toLithosphereS*
losp	Petroleum loss	*losp1C*	*fromPetroleumC*	*toLithosphereC*
		losp1N	*fromPetroleumN*	*toLithosphereN*
		losp1S	*fromPetroleumS*	*toLithosphereS*
ndep	Atmos. deposition of N	*ndep1N*	*fromAtmosnecN*	*toSoilN*
		ndep2N	*fromAtmosnecN*	*toOceannecN*
nexc	N extracelluar release	*nexc1N*	*fromOceanpandcN*	*toOceanhumusN*
nexp	Export of N to the oceans	*nexp1N*	*fromSoilN*	*toOceannecN*
		nexp2N	*fromSoilN*	*toOceanhumusN*

Table 8.2 Biogeochemical Processes and Flows included in the Dynamic Global Biogeochemical Cycling Model (Cont.)

Process code	Process name	Flow code	From Stock	To Stock
nibr	Deep burial of inorganic N sediments	*nibr1N*	*fromOceannecN*	*toLithosphereN*
nobr	Deep burial of organic N sediments	*nobr1N*	*fromOceanhumusN*	*toLithosphereN*
nomo	N mortality of marine prdcrs & cnsmrs	*nomo1N*	*fromOceanpandcN*	*toOceanhumusN*
norg	Organic matter N processing	*norg1N*	*fromOceanhumusN*	*toOceannecN*
nrot	N litter decomposition	*nrot1N*	*fromDetritusN*	*toSoilN*
nsol	Other soil N processing	*nsol1N*	*fromSoilN*	*toAtmosnecN*
ntmo	N terrestrial litterfall & mortality	*ntmo1N*	*fromVegezoomasN*	*toDetritusN*
ntse	Sedimentation of organic N in soils	*ntse1N*	*fromSoilN*	*toLithosphereN*
nwet	Weathering of N crustal rocks	*nwet1N*	*fromLithosphereN*	*toSoilN*
nwfs	N soil wildfires	*nwfs1N*	*fromSoilN*	*toDetritusN*
		nwfs2N	*fromSoilN*	*toAtmosn2N*
		nwfs3N	*fromSoilN*	*toAtmosnecN*
nzpr	N other zoomass processes	*nzpr1N*	*fromVegezoomasN*	*toAtmosnecN*
		nzpr2N	*fromVegezoomasN*	*toDetritusN*
occp	$CaCO_3$ production	*occp1C*	*fromOceannecC*	*toOceancalccarbC*
occr	Remineralisation of $CaCO_3$	*occr1C*	*fromOceancalccarbC*	*toOceannecC*
ocpr	Marine consumer production	*ocpr1C*	*fromOceanhumusC*	*toOceanpandcC*
		ocpr1N	*fromOceanhumusN*	*toOceanpandcN*
		ocpr1P	*fromOceanhumusP*	*toOceanpandcP*
		ocpr1S	*fromOceanhumusS*	*toOceanpandcS*
		ocpr2C	*fromOceanhumusC*	*toOceannecC*
		ocpr2N	*fromOceanhumusN*	*toOceannecN*
		ocpr2P	*fromOceanhumusP*	*toOceannecP*
		ocpr2S	*fromOceanhumusS*	*toOceannecS*
oden	Ocean denitrification	*oden1C*	*fromOceanhumusC*	*toOceannecC*
		oden1N	*fromOceanhumusN*	*toAtmosn2N*
		oden1P	*fromOceanhumusP*	*toOceannecP*
		oden1S	*fromOceanhumusS*	*toOceannecS*
		oden2N	*fromOceanhumusN*	*toAtmosnecN*
		oden3N	*fromOceannecN*	*toAtmosn2N*
		oden4N	*fromOceannecN*	*toAtmosnecN*
onpp	Ocean NPP	*onpp1C*	*fromOceannecC*	*toOceanpandcC*
		onpp1N	*fromAtmosn2N*	*toOceanpandcN*
		onpp1P	*fromOceannecP*	*toOceanpandcP*
		onpp1S	*fromOceannecS*	*toOceanpandcS*
		onpp2N	*fromOceannecN*	*toOceanpandcN*
pexc	P extracelluar release	*pexc1P*	*fromOceanpandcP*	*toOceanhumusP*
pexp	Export of P to the oceans	*pexp1P*	*fromSoilP*	*toOceanhumusP*
		pexp2P	*fromSoilP*	*toOceannecP*
pibr	Deep burial of inorganic P sediments	*pibr1P*	*fromOceannecP*	*toLithosphereP*
plit	Lithification of inorganic P soils	*plit1P*	*fromSoilP*	*toLithosphereP*
pobr	Deep burial of organic P sediments	*pobr1P*	*fromOceanhumusP*	*toLithosphereP*
poem	PO_4^{3-} ocean emissions	*poem1P*	*fromOceannecP*	*toSoilP*
pomo	P mortality of marine prdcrs & cnsmrs	*pomo1P*	*fromOceanpandcP*	*toOceanhumusP*
porg	Organic matter P processing	*porg1P*	*fromOceanhumusP*	*toOceannecP*
prot	P litter decomposition	*prot1P*	*fromDetritusP*	*toSoilP*
psem	PO_4^{3-} soil emissions	*psem1P*	*fromSoilP*	*toOceannecP*
ptmo	P terrestrial litterfall & mortality	*ptmo1P*	*fromVegezoomasP*	*toDetritusP*
ptse	Sedimentation of organic P in soils	*ptse1P*	*fromSoilP*	*toLithosphereP*

Table 8.2 Biogeochemical Processes and Flows included in the Dynamic Global Biogeochemical Cycling Model (Cont.)

Process code	Process name	Flow code	From Stock	To Stock
pwet	Weathering of P crustal rocks	*pwet1P*	*fromLithosphereP*	*toSoilP*
pwfs	P soil wildfires	*pwfs1P*	*fromSoilP*	*toDetritusP*
pzpr	P other zoomass processes	*pzpr1P*	*fromVegezoomasP*	*toDetritusP*
sdep	Atmos. deposition of S	*sdep1S*	*fromAtmosnecS*	*toSoilS*
		sdep2S	*fromAtmosnecS*	*toOceannecS*
sexc	S extracelluar release	*sexc1S*	*fromOceanpandcS*	*toOceanhumusS*
		sexc2S	*fromOceanpandcS*	*toAtmosnecS*
sexp	Export of S to the oceans	*sexp1S*	*fromSoilS*	*toOceanhumusS*
		sexp2S	*fromSoilS*	*toOceannecS*
sibr	Deep burial of inorganic S sediments	*sibr1S*	*fromOceannecS*	*toLithosphereS*
sobr	Deep burial of organic S sediments	*sobr1S*	*fromOceanhumusS*	*toLithosphereS*
soem	Oceanic sea salt SO_4^{2-} emissions	*soem1S*	*fromOceannecS*	*toAtmosnecS*
somo	S mortality of marine prdcrs & cnsmrs	*somo1S*	*fromOceanpandcS*	*toOceanhumusS*
sorg	Organic matter S processing	*sorg1C*	*fromOceanhumusC*	*toAtmosnecC*
		sorg1S	*fromOceanhumusS*	*toOceannecS*
		sorg2S	*fromOceanhumusS*	*toAtmosnecS*
srot	S litter decomposition	*srot1S*	*fromDetritusS*	*toSoilS*
ssol	Other soil S processing	*ssol1C*	*fromSoilC*	*toAtmosnecC*
		ssol1S	*fromSoilS*	*toAtmosnecS*
stem	Aeolian emissions of SO_4^{2-} aerosols	*stem1S*	*fromSoilS*	*toAtmosnecS*
stmo	S terrestrial litterfall & mortality	*stmo1S*	*fromVegezoomasS*	*toDetritusS*
stse	Sedimentation of organic S in soils	*stse1S*	*fromSoilS*	*toLithosphereS*
swet	Weathering of S crustal rocks	*swet1S*	*fromLithosphereS*	*toSoilS*
swfs	S soil wildfires	*swfs1S*	*fromSoilS*	*toDetritusS*
		swfs2S	*fromSoilS*	*toAtmosnecS*
szpr	S other zoomass processes	*szpr1S*	*fromVegezoomasS*	*toDetritusS*
tden	Soil denitrification	*tden1C*	*fromSoilC*	*toAtmosnecC*
		tden1N	*fromSoilN*	*toAtmosn2N*
		tden2N	*fromSoilN*	*toAtmosnecN*
tfix	Terrestrial N_2 fixation (excl. agriculture)	*tfix1N*	*fromAtmosn2N*	*toSoilN*
tnox	Release of NO_x from soils	*tnox1N*	*fromSoilN*	*toAtmosnecN*
tnpp	Terrestrial NPP (excl. crops)	*tnpp1C*	*fromAtmosnecC*	*toVegezoomasC*
		tnpp1N	*fromDetritusN*	*toVegezoomasN*
		tnpp1P	*fromDetritusP*	*toVegezoomasP*
		tnpp1S	*fromDetritusS*	*toAtmosnecS*
		tnpp2N	*fromSoilN*	*toVegezoomasN*
		tnpp2P	*fromSoilP*	*toVegezoomasP*
		tnpp2S	*fromDetritusS*	*toVegezoomasS*
		tnpp3S	*fromSoilS*	*toAtmosnecS*
		tnpp4S	*fromSoilS*	*toVegezoomasS*
wfve	Vegetation wildfires	*wfve1C*	*fromVegezoomasC*	*toAtmosnecC*
		wfve1N	*fromVegezoomasN*	*toAtmosn2N*
		wfve1P	*fromVegezoomasP*	*toDetritusP*
		wfve1S	*fromVegezoomasS*	*toAtmosnecS*
		wfve2C	*fromVegezoomasC*	*toDetritusC*
		wfve2N	*fromVegezoomasN*	*toAtmosnecN*
		wfve2S	*fromVegezoomasS*	*toDetritusS*
		wfve3C	*fromVegezoomasC*	*toLithosphereC*
		wfve3N	*fromVegezoomasN*	*toDetritusN*

8.3.3 Flow Rate Equations

First order rate equations

In chemistry, a first order rate equation is one that depends usually on the concentration (or pressure) of just one reactant or product. Under this approach the rate of a chemical reaction, *r*, is defined as,

$$r = k[\mathrm{A}]^x ,$$

where $[\mathrm{A}]$ is the concentration of a chemical species, x is equal to one, and k is the rate coefficient or rate constant of the reaction. Functions of this form are also often utilised in dynamic modelling, particularly in equilibrium seeking or stabilising models, as it establishes a type of self-regulating relationship. The Mackenzie *et al*. (1993) and GBCM (McDonald, 2005) are examples of models based on first order rate equations. A key weakness of modelling the biogeochemical cycles in this manner is that the flow rate of a particular biogeochemical process is determined from a single donor stock. Many biogeochemical processes are however driven by multiple donor stocks (e.g. photosynthesis may be increased by either CO_2 or N fertilisation) or a combination of both donor and receptor stocks (e.g. oceanic uptake of C by the atmosphere).

Defining flow rates

In the DGBCM a 'uniform', rather than first order, rate equation is applied. An advantage of this approach is that the magnitude of a flow is determined by all contributing donor stocks i.e. first, second, third, fourth order and beyond.[163] For a given biogeochemical process, *n*, the mass of an element flowing between environmental commodity stocks is determined by first calculating a flow rate, $fluxrate_n$. The generalised equation for $fluxrate_n$ is,

$$fluxrate_n = weightstock_n \times k_n \times \prod_{m^C=1}^{\kappa_n^C} \left(Envstock_{m^C} \right)^{\omega_n^C} \times \prod_{m^N=1}^{\kappa_n^N} \left(Envstock_{m^N} \right)^{\omega_n^N} \times \prod_{m^P=1}^{\kappa_n^P} \left(Envstock_{m^P} \right)^{\omega_n^P} \times \prod_{m^S=1}^{\kappa_n^S} \left(Envstock_{m^S} \right)^{\omega_n^S} , \quad (8.1)$$

[163] It does not however address the issue of biogeochemical processes being both donor and receptor driven.

where $fluxrate_n$ refers to the ratio of the current biogeochemical flow to the base year flow (e.g. if a flow is twice the size of the base year then $fluxrate_n = 2$) and k_n is the flow constant for process n (defined in Section 8.3.5). The term $Envstock_{m^C}$ denotes a stock of environmental commodity m measured in C terms, $Envstock_{m^N}$ is a stock of commodity m measured in N terms, and so on. The term κ_n^P is the number of P commodities involved as a donor stock in the process n, while κ_n^S is the number of S commodities involved as a donor stock in that process n. The coefficient ω_n^C is defined as,

$$\kappa^C \neq 0 \Rightarrow \omega_n^C = \frac{1}{\kappa_n^C \times \tau_n} \quad ,$$
$$\kappa^C = 0 \Rightarrow \omega_n^C = 1$$

where τ_n is the number of different elements involved in the process n (maximum = 4, i.e. C, N, P, and S).

It is worth noting that if an element does not appear in the biogeochemical process n, then the part of the equation relating to that element is removed and replaced with a 1. If, for example, only C is involved in the process n then the equation becomes:

$$fluxrate_n = weightstock_n \times k_n \times \prod_{m^C=1}^{\kappa_n^C} \left(Envstock_{m^C} \right)^{\omega^C} .$$

Finally, the term $weightstock_n$ is defined as the weighted aggregation of all the donor stocks involved in process n, and is defined as,

$$weightstock_n = \sum_{m^C=1}^{\kappa_n^C} \left(Envstock_{m^C} \times SNK_{m^C,n} \right) + \sum_{m^N=1}^{\kappa_n^N} \left(Envstock_{m^N} \times SNK_{m^N,n} \right) + \sum_{m^P=1}^{\kappa_n^P} \left(Envstock_{m^P} \times SNK_{m^P,n} \right) + \sum_{m^S=1}^{\kappa_n^S} \left(Envstock_{m^S} \times SNK_{m^S,n} \right) ,$$

where $SNK_{m^C,n}$, $SNK_{m^N,n}$, $SNK_{m^P,n}$ and $SNK_{m^S,n}$ are stock normalisation constants defined in Section 8.3.5.

Using the 'Release of N_2 and N_2O from soils under denitrification' biogeochemical process, *tden*, as an example, the flow rate equation is,

$$fluxrate_{tden} = \begin{pmatrix} \left(SoilC \times SNK_{tden,nSoilC}\right) \\ +\left(SoilN \times SNK_{tden,nSoilN}\right) \end{pmatrix} \times k_{tden} \times \left(SoilC^{\frac{1}{2}} \times SoilN^{\frac{1}{2}} \right).$$

Note that the formula for $fluxrate_n$ exhibits constant returns to scale. Thus, if all donor stocks increase by a factor of, say, three, then $fluxrate_n$ would also increase by a factor of three. Once *fluxrate* is determined for a given process *n*, the stoichiometry of that process in the base year may be utilised to calculate the quantity of an element (C, N, S, or P) that either enters, or exits, a particular environmental commodity stock. In the case of the C cycle, for example,

$$fromflux^{C}_{m^C,n} = fluxrate_n \times FROMSTOIC^{C}_{m^C,n}, \text{ and}$$

$$toflux^{C}_{m^C,n} = fluxrate_n \times TOSTOIC^{C}_{m^C,n},$$

where $fromflux^{C}_{m^C,n}$ is the mass of C leaving the stock of m^C under process *n* and, similarly, $toflux^{C}_{m^C,n}$ is the mass of C entering the stock of m^C under process *n*. The parameters $FROMSTOIC^C$ and $TOSTOIC^C$ are defined from the stoichiometry of the base year flows. Thus, using the biogeochemical process *tden* again as an example,

$$fromflux^{C}_{tden,\,fromSoilC} = fluxrate_{tden} \times FROMSTOIC^{C}_{tden,\,fromSoilC},$$

$$fromflux^{N}_{tden,\,fromSoilN} = fluxrate_{tden} \times FROMSTOIC^{N}_{tden,\,fromSoilN},$$

$$toflux^{C}_{tden,AtmosnecC} = fluxrate_{tden} \times TOSTOIC^{C}_{tden,AtmosnecC},$$

$$toflux^{N}_{tden,AtmosnecN} = fluxrate_{tden} \times TOSTOIC^{N}_{tden,AtmosnecN}, \text{ and}$$

$$toflux^{N}_{tden,Atmosn2N} = fluxrate_{tden} \times TOSTOIC^{N}_{tden,Atmosn2N}.$$

With the total mass of all element flows entering, and exiting, environmental commodity stocks for a given biogeochemical process determined the only remaining task is to allocate these to specific flows, i.e. a flow from one stock to another. Specifically, each *fromflux* estimate for a particular element, stock, and process combination, is distributed among the relevant destination stocks on a pro-rata basis. Thus, in the case of the C cycle,

$$flux^{C}_{m^{C},m^{C\prime},n} = fromflux^{C}_{m^{C},n} \times \frac{toflux^{C}_{m^{C\prime},n}}{\sum_{m^{C}}^{\xi^{C}_{n}} toflux^{C}_{m^{C\prime},n}},$$

where $flux^{C}_{m^{C},m^{C\prime},n}$ is the flow of C from environmental commodity stock m^{C} (first subscript), to environmental commodity stock $m^{C\prime}$ (second subscript), for process n (third subscript), with ξ^{C}_{n} representing the number of recipient C stocks under process n. To incorporate these flows into the DBGCM requires matching processes to their corresponding flows using Table 8.2 above. So, for example, the flow of C from the *SoilC* stock to the *AtmosnecC* stock and flow of N from the *SoilN* stock to the *AtmosnecN* and *Atmosn2N* stocks associated with the *tden1C*, *tden1N* and *tden2N* biogeochemical processes are respectively defined as,

$tden1C = flux^{C}_{tden,\,fromSoilC,\,toAtmosnecC}$,

$tden1N = flux^{N}_{tden,\,fromSoilN,\,toAtmosn2N}$, and

$tden2N = flux^{N}_{tden,\,fromSoilN,\,toAtmosn2N}$.

Figures 8.2 to 8.5 show the biogeochemical stocks and flows incorporated for each of the cycles in the DBGCM, in the Vensim® System Dynamics graphical language. Note that each diagram is an independent view of the same model.

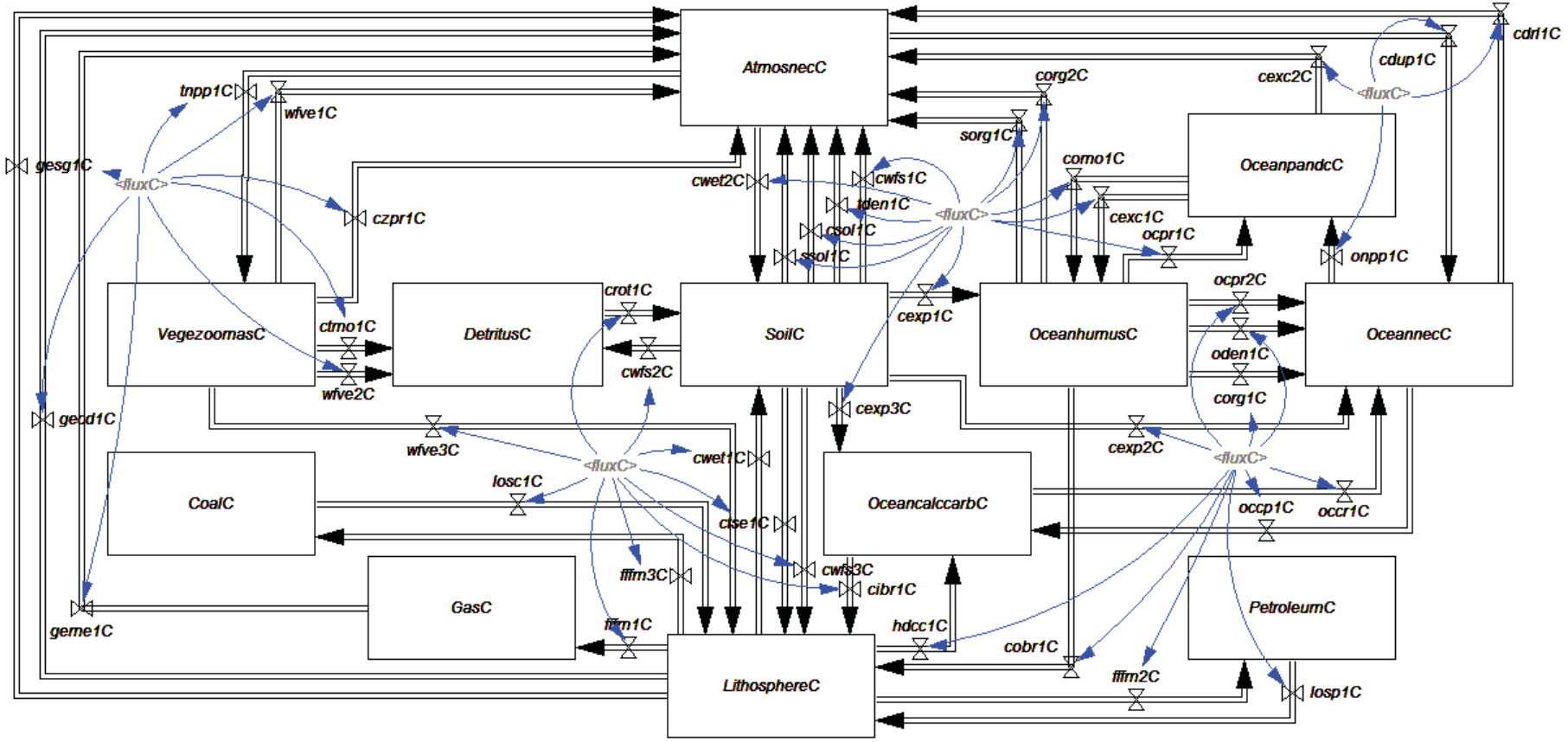

Figure 8.2 The Carbon Cycle in the Dynamic Global Biogeochemical Cycling Model

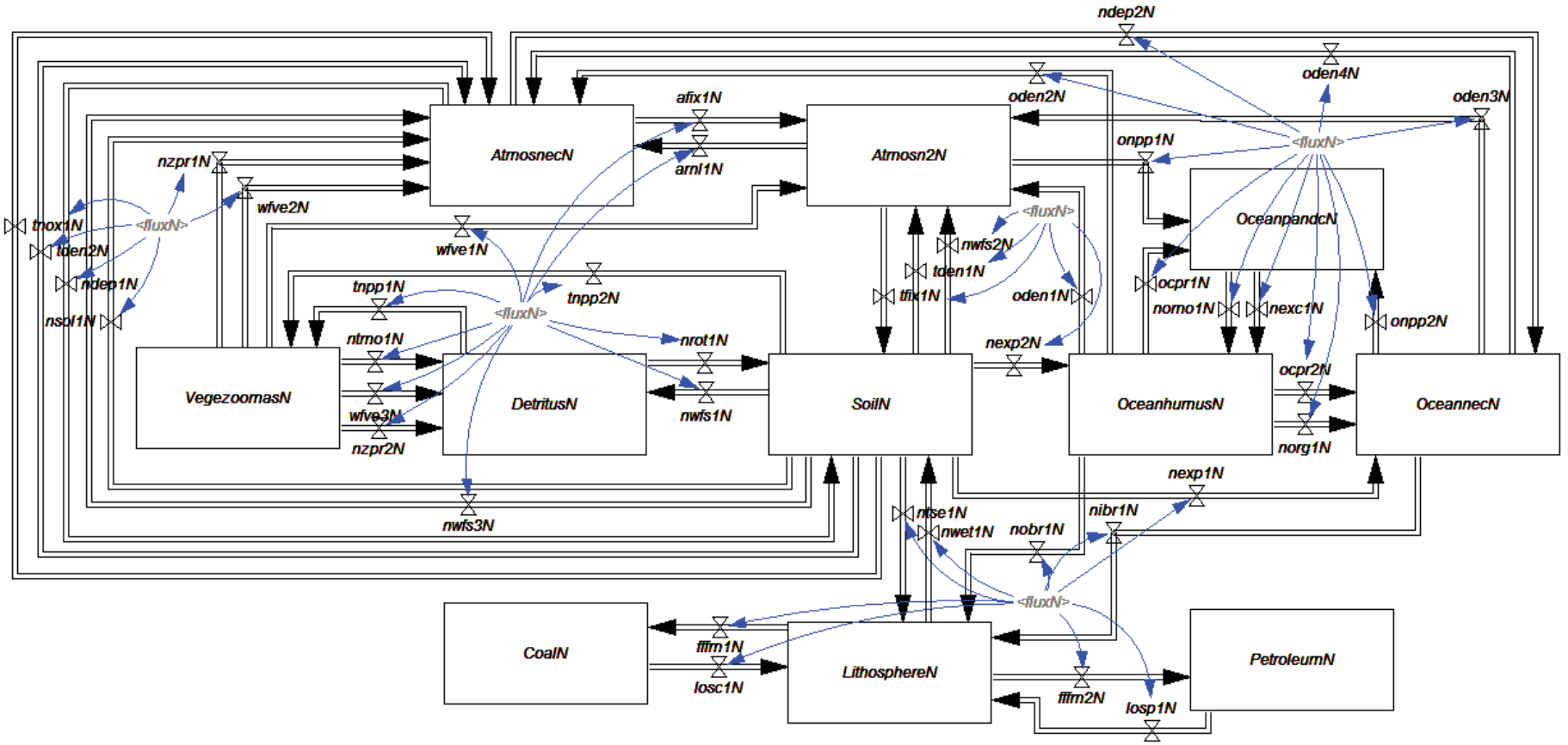

Figure 8.3 The Nitrogen Cycle in the Dynamic Global Biogeochemical Cycling Model

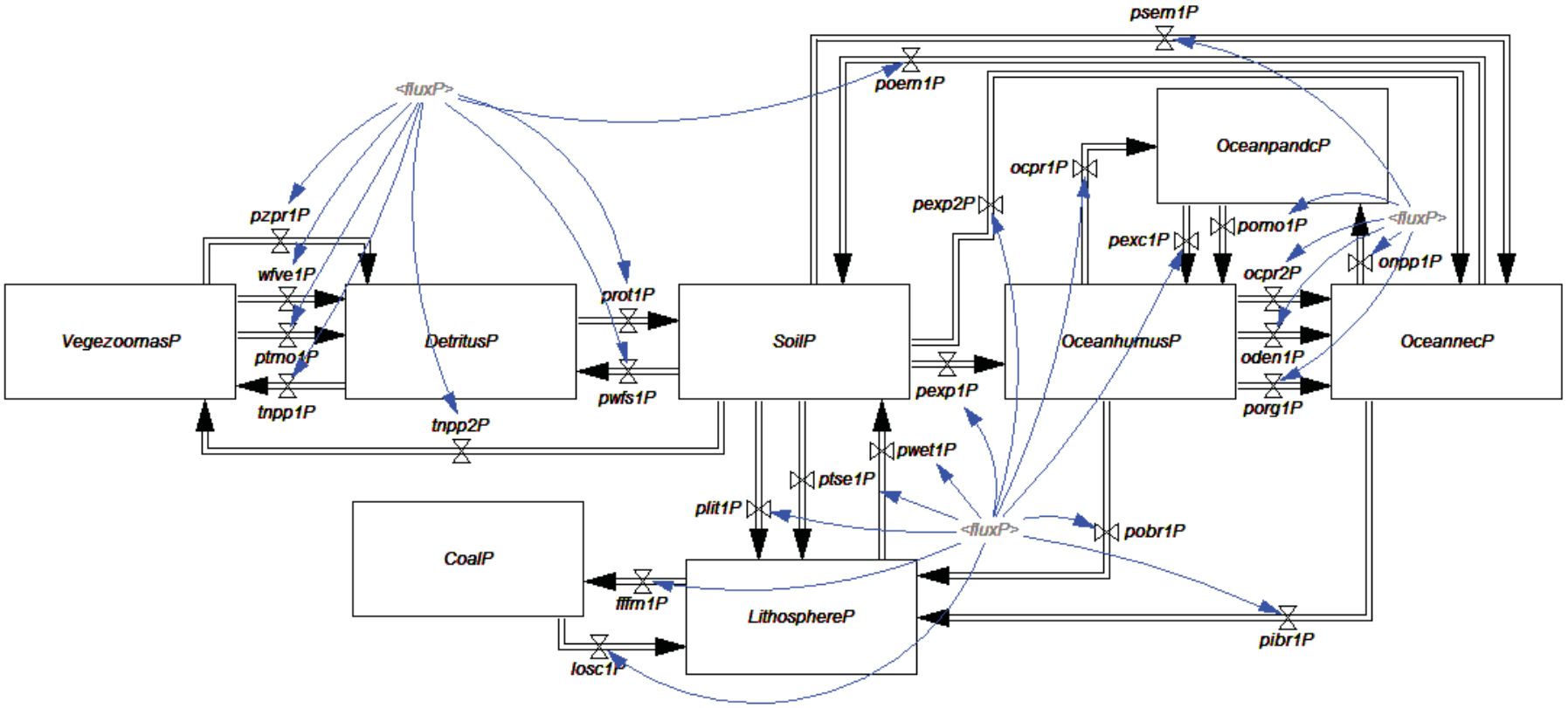

Figure 8.4 The Phosphorus Cycle in the Dynamic Global Biogeochemical Cycling Model

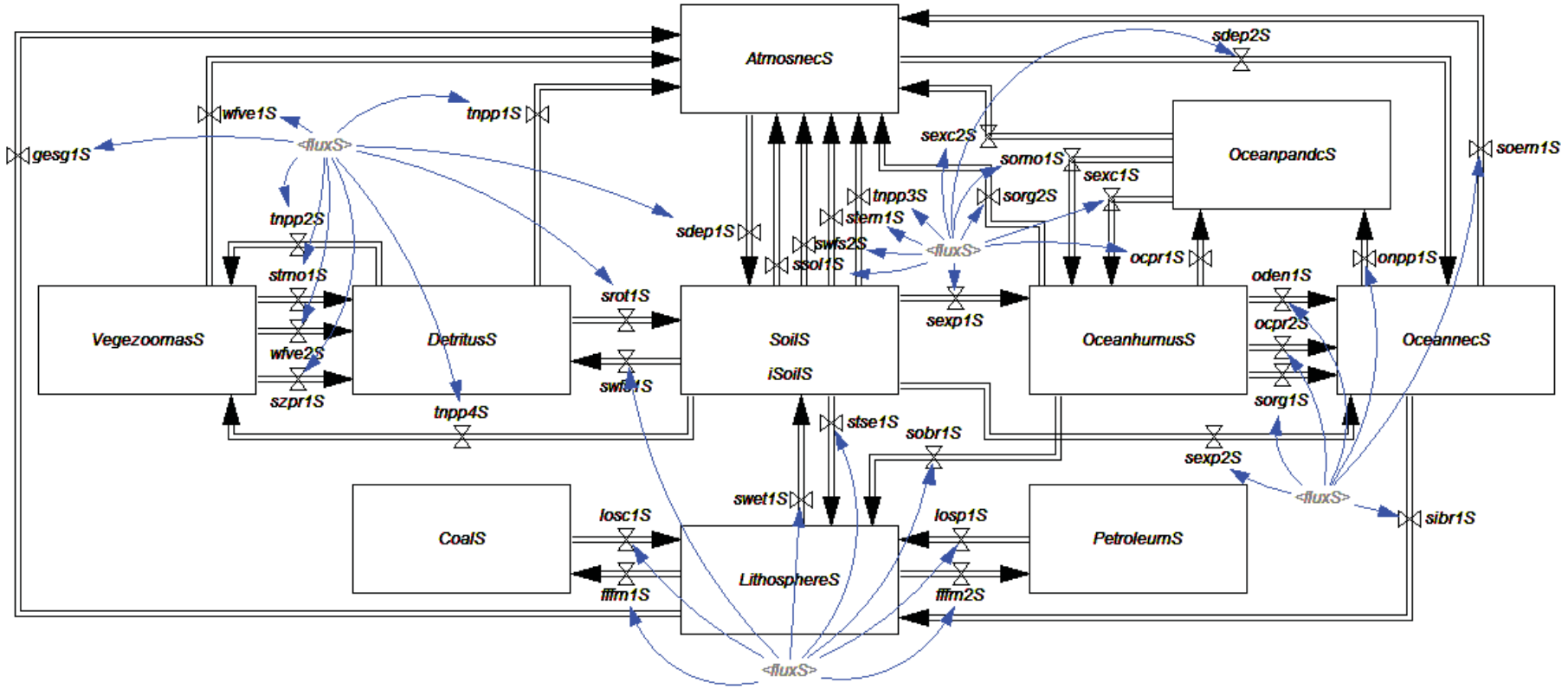

Figure 8.5 The Sulphur Cycle in the Dynamic Biogeochemical Global Cycling Model

8.3.4 Changes in Stocks over Time

The DBGCM utilises finite difference equations to keep trace of the mass of elements contained within each environmental commodity stock. The $AtmosnecC$ stock, for example, includes inputs for release of CO_2 from the oceans (i.e. $cdrl1C$), C extracellular release of organic matter by marine producers ($cexc2C$), organic matter processing C ($corg2C$), other soil processing C ($csol1C$), C soil wildfires ($cwfs1C$), C zoomass production, respiration and excretion ($czpr1C$), geological emissions of CO_2 ($gecd1C$), geological emissions of CH_4 ($geme1C$), geological emissions of S gases ($gesg1C$), organic matter process S ($sorg1C$), other soil processing ($ssol1C$), and release of N_2 and N_2O from soils under denitrification. Similarly, the $AtmosC$ stock also includes outputs for uptake of CO_2 by the oceans ($cdup1C$), weathering of C crustal rocks ($cwet2C$) and net terrestrial primary production ($tnpp$). The mass of C contained within the $AtmosnecC$ stock is thus calculated as,

$$AtmosnecC(t+dt) = AtmosnecC(t) + \begin{pmatrix} cdrl1C + cexc2C + corg2C + csol1C \\ +cwfs1C + czpr1C + gecd1C + geme1C \\ +gesg1C + sorg1C + ssol1C + tden1C \\ +wfve1C - cdup1C - cwet2C - tnpp1C \end{pmatrix} \times dt\,.$$

8.3.5 Parameters

Several constants must be defined in order to perform the equations laid out in Sections 8.3.3 and 8.3.4 above. Specifically, these include the flow constant k_n, the stock normalisation constants SNK_n, and the initial base year values for all DBGCM environmental commodity stocks.

Flow constant

The flow constant k_n is defined as follows:

$$k_n = \frac{1}{\left(\begin{array}{l} \prod_{m^C=1}^{\kappa_n^C} \left(Envstock_{m^C}(0) \right)^{\omega^C} \times \prod_{m^N=1}^{\kappa_n^N} \left(Envstock_{m^N}(0) \right)^{\omega^N} \\ \times \prod_{m^P=1}^{\kappa_n^P} \left(Envstock_{m^P}(0) \right)^{\omega^P} \times \prod_{m^S=1}^{\kappa_n^S} \left(Envstock_{m^S}(0) \right)^{\omega^S} \end{array} \right)},$$

where $Envstock_{m^C}(0)$ refers to the mass of C contained within the environmental commodity stock *m* at *t*=0, $Envstock_{m^N}(0)$ refers to the mass of N contained within the environmental commodity stock, and so on. Note, as above, if an element is not present in the biogeochemical process *n*, then the part of the equation that relates to that equation is set to 1.

Stock normalisation constants

For all C commodities involved as donor stocks in process *n*, the stock normalisation coefficient, $SNK_{m^C,n}$, is defined from base year data as,

$$SNK_{m^C,n} = \frac{\omega_n^C}{Envstock_{m^C}(0)}.$$

$SNK_{m^N,n}$, $SNK_{m^P,n}$ and $SNK_{m^S,n}$ are defined in a similar manner respectively for N, P and S commodities.

Base Year Stock Values

Appendix E Tables E.1 to E.4 provides the initial values for the environmental commodity stocks included in the DGBCM, while Appendix E Table E.5 provides a concordance matching the stocks used Chapters 4, 5, 6, and this chapter.

8.4 Steady State Analysis

With the DBGCM model equations determined, and populated with data extracted from Chapter 5 and Appendix E, it is now possible to establish the 'steady state' conditions for the model. Without the influence of anthropogenic emissions and residual generation, the DBGCM should produce environmental commodity stocks that are near constant or fluctuate within narrow bounds over time, i.e. the biogeochemical process inflows, and outflows, for each environment stock are in balance (Mackenzie *et al*., 1993; Ayres, 1996; McDonald, 2005). This reflects the self-regulating feedback loop inherent in each flow rate function (Eq. 8.1), which entails that as the stock of a commodity increases, the rate of processes depleting that stock also increase. Authors such as Ayres (1996) and Smil (2002) nevertheless have questioned the steady state assumption – at least, its long-term validity. They argue that the

biogeochemical cycles, over geological time scales, are seldom in balance – a consequence of changing orbital, tectonic, volcanic, climatic and other conditions. Nevertheless, for the past 10,000 years, environmental conditions have remained very stable, with temperatures, freshwater availability, and biogeochemical flows all remaining within relatively narrow ranges (Dansgaard *et al*., 1993; Rioual *et al*., 2001). Geologists refer to this long period of stability as the 'Holocene'. Without anthropogenic perturbation it is anticipated that the Holocene conditions would continue for at least several thousand more years (Berger and Loutre, 2002). Employing the concepts described in Section 2.4.2, we can thus view the Holocene state as a type of 'attractor' or stability domain.

The DGBCM, as developed to date, puts aside all economy stocks (e.g. crops, buildings and people) and flows – these are included in Chapter 9. Running the DGBCM into the future thus provides a crude estimate of the hypothetical steady state conditions, with anthropogenic influences on the system excluded. Figures 8.7–8.10 show, as Vensim® output graphs, the long-term trajectories for the DGBCM environmental commodity stocks under such conditions, using a 1,000 year run of the model. It should be noted that the lithosphere stocks are not included, as any changes in these stocks over the simulation period are negligible.

The figures illustrate that all environmental commodity stocks within the DGBCM head towards a long-term equilibrium, with the equilibrium state being close to the initial conditions for the majority of stocks. Differences do, however, occur between the initial and steady state conditions for some stocks, particularly those within the N cycle. There are two key reasons for this. First, as illustrated by much of the discussion in Chapter 5, our understanding of the biogeochemistry of the Earth is still very much in its infancy, and many stock and flow values are only tentatively established. Second, while the DBGCM developed this far does not include economy stocks and flows, the initial (base year) state of the environmental system reflects past influences of human activities on the system. Once biogeochemical flows brought about by human resource use and residual generation are removed the environmental system must adjust to new conditions.

Human activities over the last 120 years have, in particular, led to significant alterations in the N cycle (Galloway and Cowling, 2002). As outlined in Chapter 4, industrial N fixation and fossil fuel combustion have added huge quantities of reactive N to the biosphere. At present, human-caused creation of reactive N is at least two times larger than the rate of natural terrestrial creation (Ciais *et al*., 2013). It is perhaps not surprising that in the steady-state run

of the DGBCM, the atmospheric stock of reactive N (*AtmosnecN*) falls significantly from its base year value, until such a point that the rates of N loss from the stock matches the natural rates of reactive N emissions. Similarly, without ongoing anthropogenic addition of N to soils, the stock of soil N in the DGBCM falls away until it reaches a point where natural sinks (predominantly denitrification and river export) balance natural sources (predominantly biological and lightning N fixation and weathering).

When interpreting the above outputs from the DGBCM, it should be also noted that biological N fixation on cropland and pasture is excluded from the model, as these processes are considered among the anthropogenic flows.[164] However, in a world without human activities, we would expect some biological N fixation to occur on land presently used for agriculture, although the rates of fixation may be lower. With inclusion of these additional inputs of reactive N to the biosphere each year, the derived equilibrium values for the reactive N stocks (including *SoilN*, *OceanhumusN* and *OceannecN*) would be somewhat higher than those depicted in the above diagrams. This would also mean that, for each element, the vegetation and zoomass stock (*VegezoomasC*, *VegezoomasN*, *VegezoomasP*, *VegezoomasS*) would settle at a position closer to its initial value, being less impacted by loss of soil nutrients. This illustrates that the steady state run of the DGBCM, which excludes consideration of any anthropogenic processes, can only produce a tentative, albeit reasonable, indication of the model's behaviour.

Related to the above paragraph, it is also worth noting that the DGBCM does not include primary production on croplands, which currently accounts for around 9 percent of total NPP.[165] Cropland NPP is thus a relatively substantial sink for atmospheric C and ultimately, following use of biomass within the anthrosphere, a relatively substantial source of C to soils. If the DGBCM were to include additional NPP as a replacement for cropland NPP, we could expect the stock of C within vegetation, litter/detritus, and soils to settle at a higher equilibrium position, at the expense of a lower equilibrium position for atmospheric C.

[164] Refer to Section 4.3.5.
[165] Refer to Sections 4.3.1, 5.4.1.

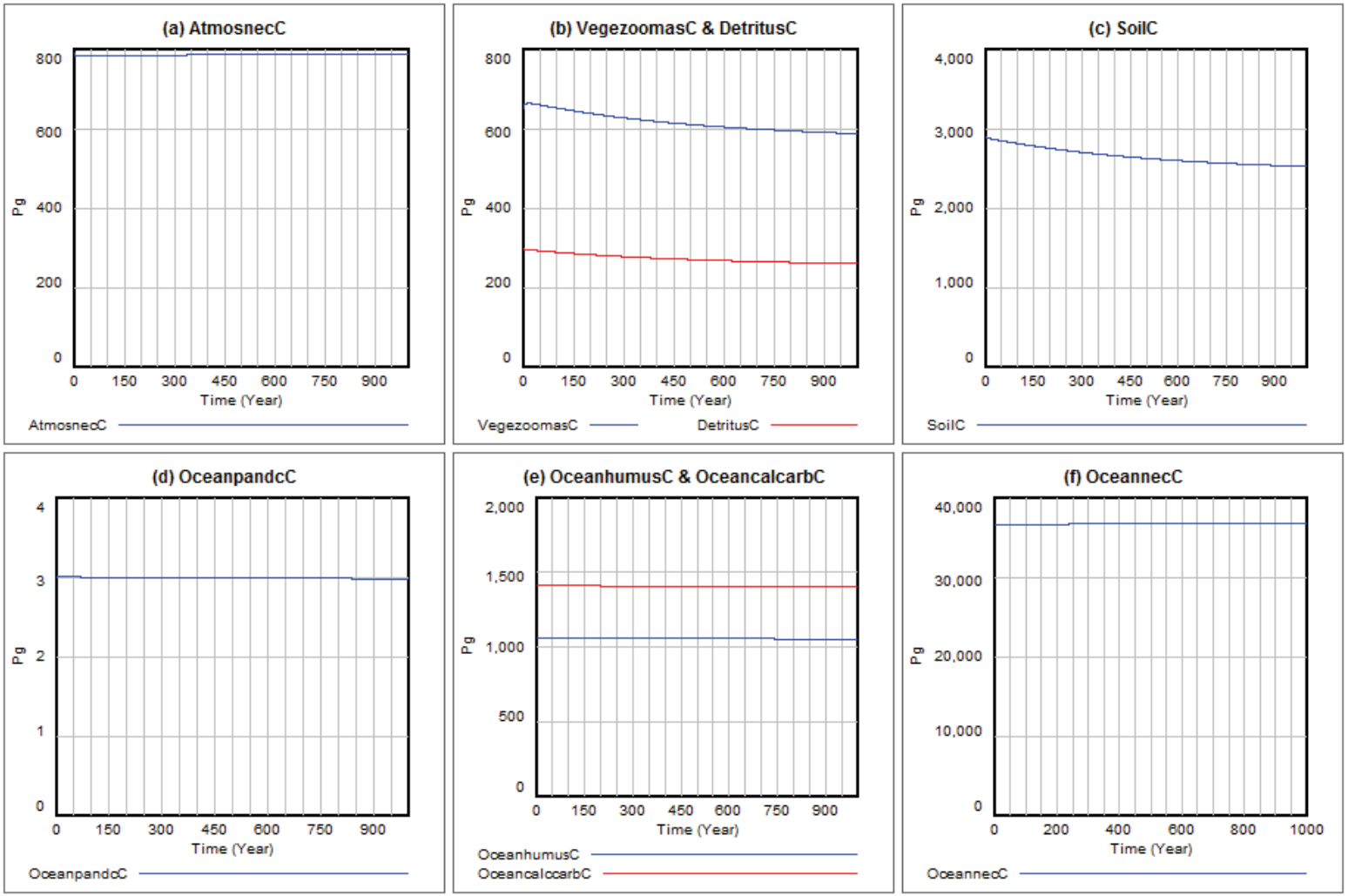

Figure 8.6 **Steady State Analysis of Carbon Stocks in the Dynamic Global Biogeochemical Cycling Model, 1000 Year Run**

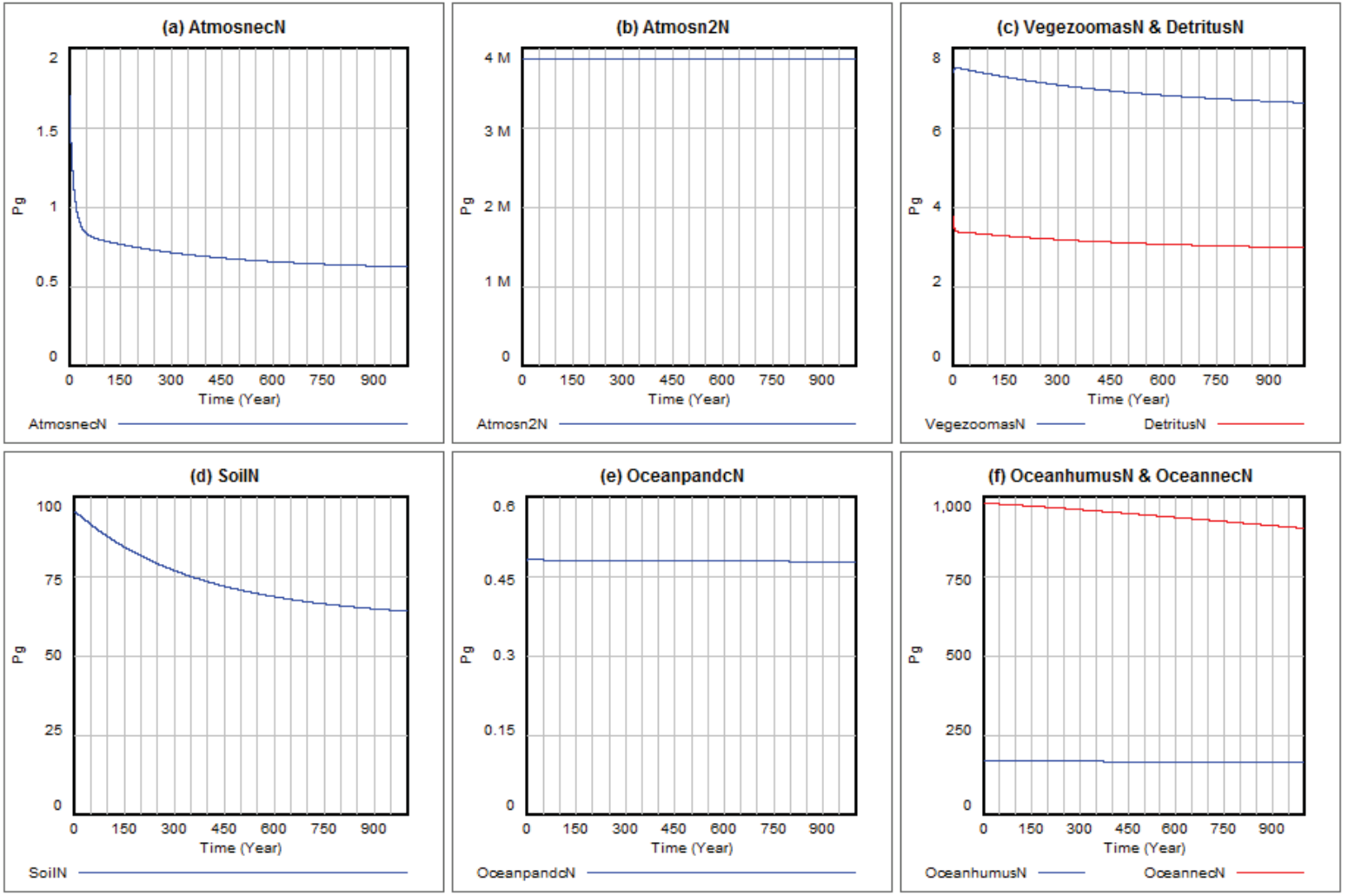

Figure 8.7 Steady State Analysis of Nitrogen Stocks in the Dynamic Global Biogeochemical Cycling Model, 1000 Year Run

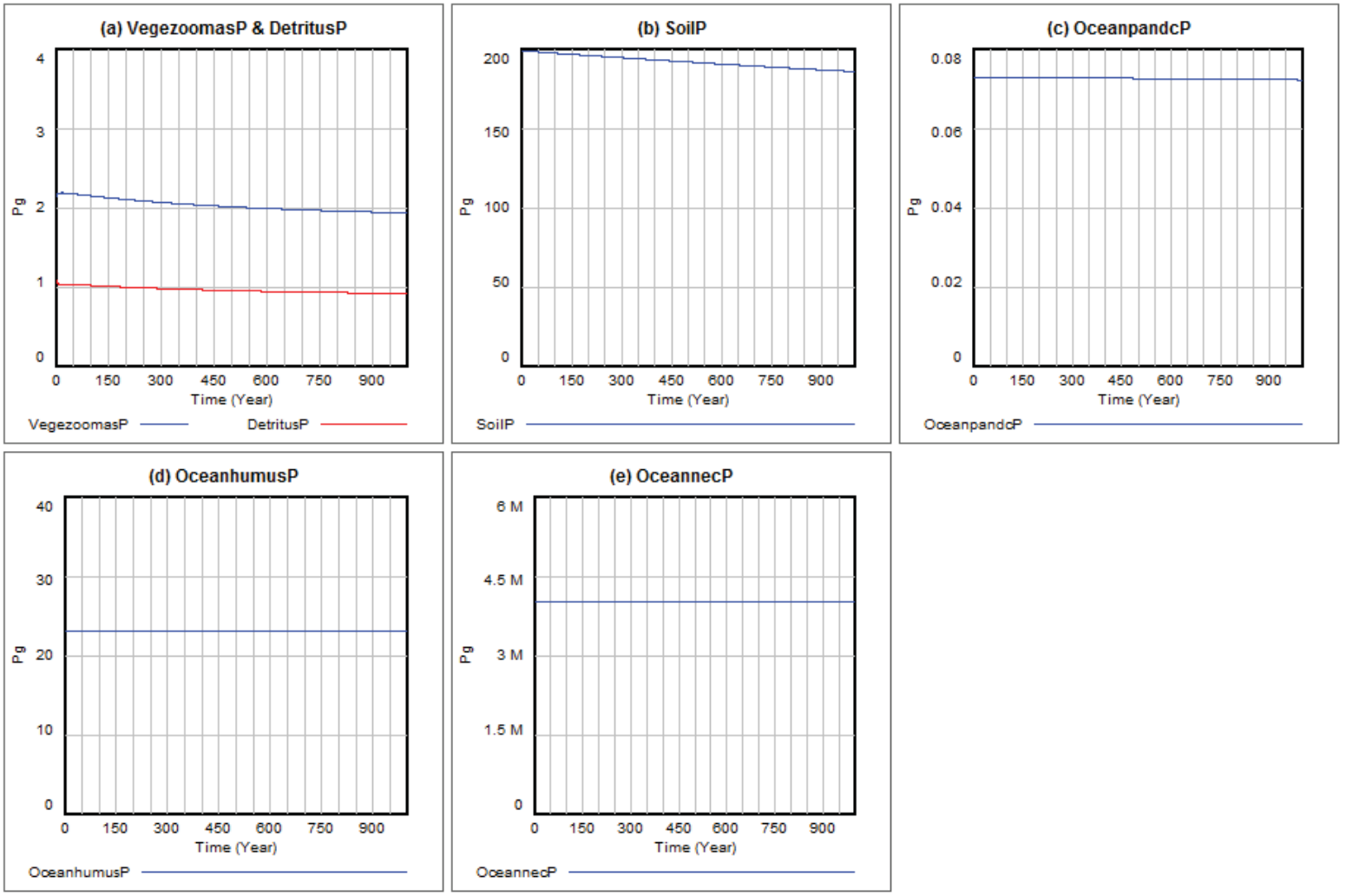

Figure 8.8 **Steady State Analysis of Phosphorus Stocks in the Dynamic Global Biogeochemical Cycling Model, 1000 Year Run**

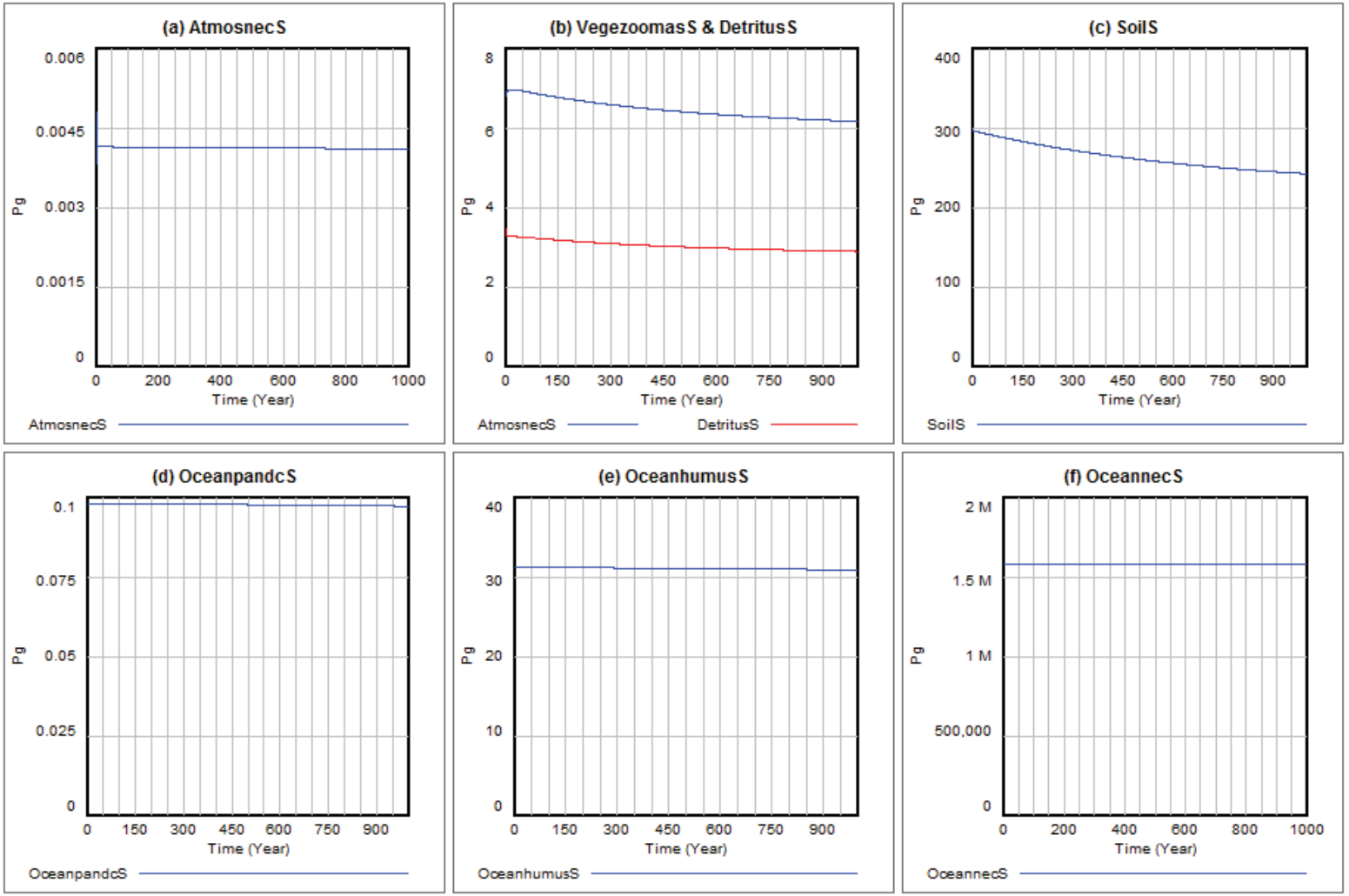

Figure 8.9 **Steady State Analysis of Sulphur Stocks in the Dynamic Global Biogeochemical Cycling Model, 1000 Year Run**

8.5 Contributions, Limitations and Areas for Future Research

This chapter has established an operational biogeochemical cycling model that not only allows for integration between the different element cycles, but also provides a key component for the Chapter 9 investigation and demonstration of relationships and feedbacks that exist between the global environment and economy systems. To this end, the model described in this chapter draws on previous modelling work undertaken primarily by McDonald (2005). There are, however, a number of key extensions to the McDonald (2005) model, namely:

(1) Selection of model stocks, processes and flows based on the detailed static analysis undertaken in Chapter 5.
(2) Related to (1), the DGBCM is intentionally constructed so that important mass flows between the environment and economy can be added, either by way of model extensions or by interfacing with another model.
(3) Alteration to the model flow equations so that flow rates (Eq. 8.1) depend on the magnitude of all relevant donor stocks, rather than on just a single donor stock.
(4) Structures within the model responsible for coupling between two or more biogeochemical cycles have been reviewed and reconfigured.[166]

There are, nevertheless, several limitations of the DGBCM as currently formulated:

- *Inclusion of other biogeochemical cycles*. This thesis has focused on the biogeochemical cycles of C, N, P and S. Nevertheless, other element cycles are critical to life support and, if degraded or depleted, could dramatically impact living organisms including humans. Of particular importance are the cycles related to hydrogen and oxygen. Water (a molecule comprised of hydrogen and oxygen) is an essential compound for life, a key transporter of materials, and a common reactant and product of many biogeochemical processes. Similarly, oxygen is often a critical element in redox (oxidation and reduction) chemical reactions. It is likely that the distribution of dissolved oxygen within the ocean will be impacted by global warming, subsequently leading to important implications for nutrient

[166] The McDonald (2005) model requires the stoichiometry of a relatively large number of the model's stocks (including living biomass stocks, terrestrial and ocean humus, sediment, and soil organic materials) to remain consistent with set element ratios. Within the DGBCM, this constraint operates only on the living biomass stocks (i.e. *Vegezoomas* and *Oceanpandc*) on the basis that there for many of the other stocks, including the various element stocks of *Detritus, Soil* and *Oceanhumus*, element ratios may feasibly change as a result of variations in the relative rates of different input and output flows.

and C cycling (Keeling *et al*. 2010).[167] Finally, there may also be other limiting elements that determine the rate of flow of a particular process, e.g. the micronutrient iron is central to the formation of enzymes required for N_2 fixation and hence impacts on the availability of N for primary production (Martin and Fitzwater, 1988; Coale *et al*., 1996). Similarly, plants require magnesium in their chloroplasts to perform photosynthesis.

- *Donor- versus receptor-determined flow rates*. One strength of the DGBCM lies in the integration of the element cycles. A key weakness, however, is that only donor stocks are utilised in the calculation of biogeochemical process flows. Several processes may, however, be better driven from a receptor stock, or combination of donor and receptor stocks, perspective, e.g. uptake of C by the oceans, release of C from the oceans, and $CaCO_3$ dissolution. Also one donor stock may have a proportionally greater influence on flow rates than other stocks. The modelling of coupled biogeochemical cycles is an area of growing research interest, particularly at the level of individual ecosystems (Rastetter, 2011). A key challenge is finding appropriate means to adapt this research for the purposes of regional- and global-scale models (Finzi *et al*., 2011).
- *Lack of any climatic feedbacks*. A key weakness of the DGBCM is that it does not take account of climate related feedbacks. Because of the short-to-medium term (<30 years) focus of the DBGCM climate feedbacks were omitted. If humanity's prevailing impact on the environment is to be better understood then a much longer view is required. In this context, of the role played by climate in biogeochemical cycling, controlling or regulating the rate at which biogeochemical processing occurs, particularly through temperature, pressure, humidity and so on.[168] Moreover, climate plays a further role in the movement/transport of material through the biosphere.
- *Energy flows.* It is commonplace for ecological models to depict not only mass, but also energy flows within ecological systems. From a conceptual perspective, the inclusion of energy flows, both within the static and the dynamic models, would help to better represent the global environment-economy structure as a 'dissipative structure' that is able to exist at a state far from equilibrium only via the continuous supply of high-quality energy. Among the important energy inputs to biogeochemical cycles are those that occur via solar radiation, gravitation, tidal flows, and crustal heat. Unfortunately, however, data

[167] It took well over a year (full-time equivalent) to construct the necessary databases (i.e. Chapters 4 and 5) for just the four elements C, N, P, and S. There is simply a limit to the number of cycles that can reasonably be considered by one person within the confines of a PhD thesis.

[168] Temperature is, for example, a critical factor in ocean atmosphere exchange of C. Moreover, climate is in itself dependent on biogeochemical processes; for example, dimethylsulfide production acts as a negative feedback loop stabilising climate.

on the extent to which many of these energy flows are captured by individual environmental and economic processes are very poor, and thus extension of the underlying static model as well as the dynamic model to represent such flows would require significant further work.[169]

- *Lack of biodiversity feedbacks*. Living organisms play a critical role in determining the distribution of elements within the planet (Schlesinger, 1997; Sterner and Elser, 2002). Changes in biogeochemical cycles, however, may also impact on the abundance and diversity of life, thus creating further flow-on impacts to biogeochemical processes. Increasing uptake of C in the oceans (ocean acidification), for example, is likely to reduce the biological production of corals as well as calcifying phytoplankton and zooplankton (Royal Society, 2005). Similarly, where N is the primary nutrient limiting plant and microbial production in terrestrial ecosystems, increases in N can result in shifts in plant species composition (Bobbink *et al*., 1998). Increased N and S deposition to forest ecosystems has also shown these systems to become more vulnerable to stress factors such as drought and pests (Heij and Schneider, 1991). Much of the research on identifying complex feedbacks between biogeochemical cycling and biodiversity is still in its infancy (Denman *et al*., 2007). Incorporating some of these key feedback structures within a model such as the DGBCM is certainly an area highlighted for significant further research.

Any attempt to extend a model such as the DGBCM to incorporate additional dynamics such as described in this section will need to balance the often-competing goals of avoiding complexity and increasing comprehensiveness. Many of the feedbacks between the C, N, S, and P cycles with other biogeochemical cycles, and changes in the climatic factors and biodiversity, will depend on the characteristics of different ecosystems, and thus will occur in an irregular pattern across space. Some system behaviours only become apparent or 'emerge' if we model structures and relationships at a relatively fine scale. A number of models presently in use for analysis of global change deal with this complexity by including significant spatial resolution. For example, the IMAGE model described above utilises a 0.5 x 0.5 degree spatial grid across the globe. General circulation models used for simulating atmosphere and ocean dynamics, particularly for climate analysis, incorporate extremely high spatial definition.

[169] Adaption of the ESAM to include energy flows would require, for example, the quantification of gravitational energy flows necessary for river nutrient transport and settling/sorting of ocean sediments, the crustal heat necessary for fossil fuel formation, the solar energy driving atmospheric transport of salts, and so on.

Aside from the considerable resources required to build models of significant spatial resolution, adding such level of detail to a model can sometimes be unhelpful, depending on the purpose of model building. In terms of ecological and economic systems, Costanza and Ruth (1998, p.184) explain that the purposes for modelling can vary from "developing simple conceptual models, in order to provide a general understanding of system behaviour, to detailed realistic applications aimed at evaluating specific policy proposals." This research on biogeochemical cycles is situated more towards the first part of the spectrum, where scoping of the nature and extent of problems, testing theories, and consensus building are particularly important. For this to be achieved, a model must be relatively general and sufficiently able to reduce the complexity of the real world. A similar idea is also captured by Meadows and Robinson (2007, p.39) who state that "[b]oth the philosophy and the general-understanding purpose of the System Dynamics method require simplicity and transparency, so that reasons for the model's behaviour can be understood."

It is acknowledged that more precise models of biogeochemical cycling could (and should) be developed in the future, particularly if these are to be used to inform the selection of actual policy options and decisions. Ideally, dynamic modelling is also undertaken as an iterative process, where general patterns of behaviour learnt from modelling undertaken at fine levels of resolution are used to continuously update and revise more general, scoping, and consensus-building models. This approach is one possible pathway for future research that builds on not only the DGBCM, but also on the broader Ecocycle model described in the next chapter.

Chapter 9

Towards an Integrated Environment-Economy Model of Global Biogeochemical Cycles

9.1 Introduction

This, the final chapter of the thesis apart from the Conclusion, is devoted to bringing the dynamic environment and economy models set out in Chapters 7 and 8 (i.e. the DGES and GBCM models respectively) into a single model of the Earth's biogeochemical cycles. Hereafter this model is referred to as the 'Ecocycle' model. As an entire thesis could be devoted to this topic, the chapter is constrained to describing only a prototype version of Ecocycle, capable of demonstrating a 'proof of concept' for integrated modelling of the Earth's biogeochemical cycles. As acknowledged in the concluding sections on each of the DGES and GBCM models, there are many opportunities to further improve the dynamic models for each of the economic and environmental systems. Some possibilities for future research are also noted in this chapter. Significant further work also needs to be undertaken in regards to model validation, verification, and uncertainty testing. Nevertheless, even at this stage of development, Ecocycle is capable of demonstrating meaningful behaviours that help further our understanding of the environment-economy system, build consensus on the importance of biogeochemical cycling within the sustainability debate, and begin to conceptualise possible pathways towards sustainability. Ecocycle is presented as a System Dynamics model, developed in the Vensim DSS® software package, in the Chapter 9 directory of the accompanying CD-ROM. The program code for the model, Ecocycle.txt, is also contained within this directory.

To begin, Section 9.2 of this chapter sets out some core extensions to the DGES model incorporated within the economic components of Ecocycle. Next, Section 9.3 describes the equations within Ecocycle that allow for integration between the economic and environmental components of the model, while Section 9.4 describes data sources employed in setting key model parameters. Two trial scenarios are set out in Section 9.5, along with modelled results for these scenarios. Key points of discussion drawn from the scenario analysis, as well as a summary of model caveats are provided respectively in Sections 9.6 and 9.7. These last two

sections thus help conclude the thesis, bringing together core findings and directions for future research.

9.2 Extending the Dynamic General Equilibrium-*Seeking* Model

The system of economic production within the DGES model, as set out in Chapter 7, can be conceptualised as a nested series of CES, CET and Leontief-type functions (Figure 9.1).[170] Three core extensions to this production system are incorporated within the Ecocycle model:

(1) Allowance for substitution between different types of energy commodities in the consumption of energy;
(2) Separation of crops into two types, food and fibre crops and biofuel crops, with allowance for possible variations in the relative supply of these crops;
(3) Separation of capital into two forms, land and other, and the addition of constraints on total agricultural land supply.

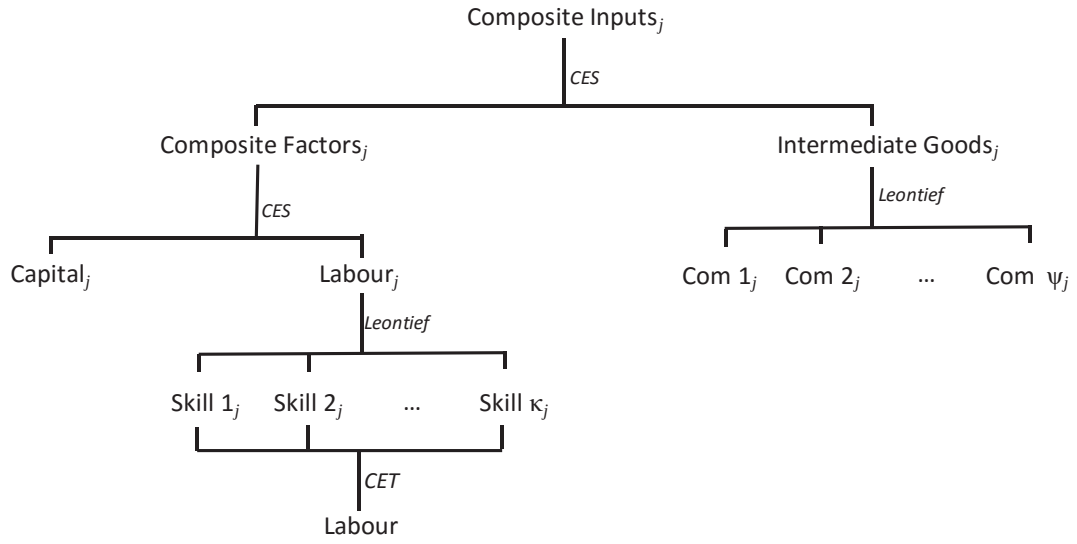

Figure 9.1 System of Production for a given Industry *j* under the Dynamic General Equilibrium-*Seeking* Model

Notes: CES = Constant elasticity of substitution function, CET = constant elasticity of transformation function, and Leontief = Leontief function

[170]The latter function type is also referred to as the 'fixed proportions production function' as it implies there is no substitutability between inputs.

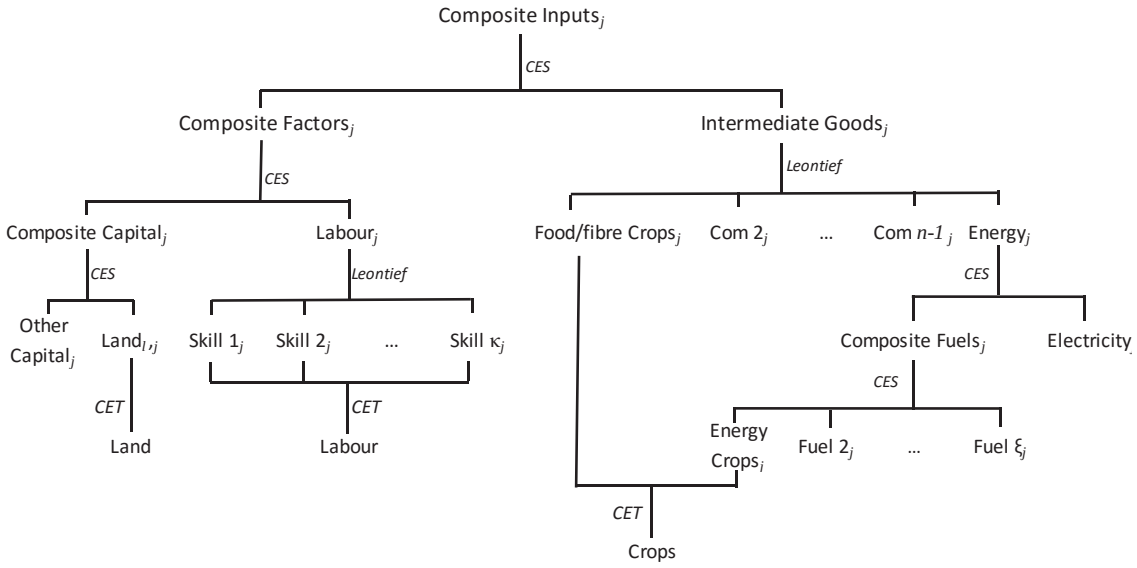

Figure 9.2 System of Production for a given Industry *j* under the Ecocycle Model

Notes: CES = Constant elasticity of substitution function, CET = constant elasticity of transformation function, and Leontief = Leontief function.

The extension of the production structure from that shown in Figure 9.1 to that shown in Figure 9.2 involves repetition of the same pricing relationships already described in Chapter 7. Thus, only a brief explanation is provided here, with a full list of equations available in Appendix G. It is worth noting that the integration of these changes into the model requires alteration of certain arrays referenced within the model's equations. Of most importance is the identification of two separate sets of commodities. The first or 'full' commodity set (subscript i) contains a complete list of all commodities covered by the model, including separate identification of each energy commodity (e.g. gas, petroleum, coal), and an aggregate crops commodity. Under the second or 'short' set (subscript i*), however, all energy commodities (including biofuel crops) are replaced by a single commodity referred to as 'composite energy'. The majority of equations involving commodities within the model continue to use the full commodity array. However, where an equation relates to consumption of commodities, either by industries, households, government or investment sectors, the short commodity array is employed. For example, Eq. 7.52 defining household consumption of commodities is replaced by the equation,

$$hhldconsump_{i^*} = hhldexpend \times \frac{HCSP_{i^*}}{pcomdshortactfd_{\text{hhlds},i^*}}. \qquad (9.1)$$

Commodity prices are also defined for both the full and short commodity.[171] Thus, the converter $pcomd_i$ is renamed '$pcomdfull_i$', while the converter $pcomdshortactfd_{\gamma,i*}$ appearing in Eq. 9.1 defines the demand price for short commodities as faced by industries and final demand sectors. To this end, the new subscript γ refers to an element of the set of industries and final demand sectors ($\gamma \in \{\text{Ind1, Ind2, ... Ind}\psi\text{, Hhlds, Govnt, Savgs}\}$).

9.2.1 Energy Input Substitution

A core finding from Chapters 4, 5, and 6 is that the biogeochemical cycles, particularly the C cycle, are heavily impacted by the ongoing consumption of energy commodities. Future trends in the demand and supply of these commodities are thus critical to the problem of sustainability. Of particular importance is the degree to which future energy demands are satisfied out of long-resident stocks of ecological commodities (fossil fuels), compared with other ecological commodities subject to more rapid cycling process. Ongoing improvements in energy efficiency, as well as substitution of C-based fuels for alternatives (e.g. wind, solar), are also important.

Many of the CGE models incorporating specific consideration of energy consumption treat energy as a factor of production, analogous to labour and capital. In this first 'prototype' Ecocycle model, however, energy commodities remain alongside other types of economic commodities, within the intermediate goods production nest. The rationale behind this approach is that it enables model users to easily devise and test scenarios involving targeted variations in the C-based energy efficiency of production, which may involve alteration of the input coefficients for other types of intermediate goods. Nevertheless, alternative nesting structures could certainly be investigated in future versions of the model.

The energy module within the Ecotime model (refer to Section G.1 within Appendix G) describes the production of a composite energy good via a nested CES-type framework. Within the first 'layer' of production, a composite fuels good combines with electricity to form the overall composite energy commodity. Thus, in a similar manner to the calculation of relative demands for factors and intermediate goods set out in Chapter 7,[172] the relative demand for electricity and composite fuels is dependent on the relative prices of these

[171] See Eqs. G.21–G.23.
[172] See Eqs. 7.11, 7.12.

different types of energy, compared with the composite energy price, and the elasticity of substitution between electricity and composite fuels.[173] Given that electricity is a unique commodity covered within the full commodities array, the price for electricity is available directly from the commodities module. In the case of the composite items, however, the relevant prices are obtained by continuously updating a price stock to reflect changes in the price of underlying inputs to that composite item.[174,175]

Within the next layer of the production nest, composite fuels are produced via the input of a range of fuel types, including conventional fuels such as oil, gas and coal, as well as biofuel crops. Once again, a first-order solution to the CES function determines the relative demands for these different fuels.[176] Note that the prices for fuels are simply the commodity prices calculated for fuel commodities (e.g. petroleum, coal, gas) within the commodities module. As one exception, however, the price of biofuel crops is specifically calculated within the commodities module and is different from the average price for all crop commodities (refer also to Section 9.2.2 below).

9.2.2 Crop-type Supply Substitution

The disaggregation of crop commodities is essential if we are to capture the often-competing demands within the global economy for the outputs of agricultural activities. The Ecotime commodities module (refer to Section G.2 in Appendix G) therefore contains a new CET-function capturing the alternative types of crop production, energy or food and fibre, possible by the crops industry. Using an approach analogous to that employed in the labour module of the DGES model, the total available supply of goods from the crops industry is shared among biofuel crops and food and fibre crops based on the relative prices of those commodities and the elasticity of transformation.[177] Like the prices for other commodities, the prices of biofuel and food and fibre crops continuously change over time in response to the relative supply of

[173] See Eqs. G.1–G.5.
[174] See Eqs. G.6–G.13.
[175] Note that it is also necessary to account for differences, relating to different tax rates, in the demand price faced by industries and final demand sectors for the composite energy commodity. This is achieved through application of a price normalisation coefficient, $PNORMCOEF_{\gamma}$ (See Eq. G.17).
[176] See Eqs. G.14–G.16.
[177] See Eqs. G.18–G.20.

and demand for those commodities.[178] In turn, the demand for these crops is calculated from the sum of industry, household, government, and investment demands.[179]

9.2.3 Capital Input Substitution and Land Constraints

As presently formulated, the DGES model treats all capital items employed by agricultural industries as potentially unlimited, as these can accumulate over time through ongoing investment of income into capital. However, land is a special type of capital employed by agricultural industries that cannot accumulate in this manner. Another important reason for tracking agricultural land is that changes in the use of land for food, fibre, and energy production may impact on the rates of biogeochemical processes covered within the environmental components of the Ecotime model.

A stock of agricultural land, *Agriland*, is added to the capital module, which may change over time according to an exogenous rate of net land conversion.[180] As with the supply of labour and crops, a CET functional form is then used to share total land supply amongst two possible uses, cropland and grazing land.[181] This means the share of land allocated to either crops or grazing is dependent on the going (rental) price for that land type compared with the average agricultural land price, and the elasticity of transformation. As with other inputs at the base of the 'production nest', the average price for land changes over time in response to differences between the supply and demand for that factor.[182] The specific prices for cropland and grazing land are determined by the respective prices of land capital for the crops (CropsA) and animals and unprocessed animal products (AnimsA) industries.[183,184]

The equations determining the supply of other forms of capital remain the same as in the original DGES model. However, the stock of capital held by each *j* industry is now renamed '$Buildcapital_j$', to indicate that it relates only to non-land capital. Within the two agricultural industries, the supply of land capital and other capital combine to form the supply of

[178] See Eqs. G.24–G.28.
[179] See Eqs. G.21, G.22.
[180] See Eqs. G.54, G.55.
[181] See Eqs. G.49, G.50.
[182] See Eqs. G.35–G.39.
[183] See Eqs. G.40-G.44.
[184] Note also that these prices, respectively $Pcapt_{\mathrm{LandC,CropsA}}$ and $Pcapt_{\mathrm{LandC,AnimsA}}$, are normalised to the value of one at the base year. The prices must therefore be scaled by the *CLCONVERT* and *GLCONVERT* constants before use in the CET function for land supply (Eq. G.49).

composite capital. For the non-agricultural industries, the supply of composite capital is simply the stock $Buildcapital_j$.[185]

Turning now to capital demands, the total demand for composite capital by an industry is as an input from the factors module via the converter $factorsd_{\mathrm{Cap},j}$. For the two agricultural industries, a first-order solution to the CES function for composite capital then determines the way in which this composite capital demand is shared among land and other forms of capital, based on the relative prices of these capital types compared with the composite capital price, and the elasticity of substitution between land and other capital.[186] The composite capital price for an industry, $Pfact_{\mathrm{Cap},j}$, is also an input from the factors module.[187]

Note that a few alterations are also necessary to the factors module in order to fully integrate the revised treatment of capital within the Ecotime model (refer to Section G.4 in Appendix G). Most important, the factor capital is now a composite item, and therefore the equations determining the price of capital for a particular industry, $Pfact_{\mathrm{Cap},j}$, are changed so as to be consistent with the equations used for other composite items.[188]

9.3 Integration of the Dynamic General Equilibrium-*Seeking* Model and the Dynamic Biogeochemical Cycling Model

This section focuses on describing the equations within the Ecotime Model that allow the economic components of the model (predominantly defined in monetary units) to interface with the bio-physical components of the model (predominantly defined in element mass units). This description is broken into three sub-sections dealing respectively with (1) environmental reserves, (2) economic resource use and residual generation and (3) improvements in input efficiency.

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[185] See Eq. G.52.
[186] See Eq. G.45.
[187] With regards to the capital module, a further point to note is that land is recorded in both an area-based unit of the land 'stock', and a monetary-based unit of the land 'flow'. The constant $LDCONVERT_j$, recording the base year flow of capital endowment, per area of land ($/m^2), enables conversion between stock and flow measurements. Similarly, the constant $KSFCONVERT_j$ is used to switch between stock and flow measurements of other capital. Together $LDCONVERT_j$ and $KSFCONVERT_j$ replace the constant $SFCONVERT_j$ used in the original DGES model.
[188] See Eqs. G.66–G.72.

9.3.1 Reserves

Although the term 'reserve' is normally employed in the context of minerals and fossil fuels (i.e. mined resources), in this chapter the term is applied generally to the stock of any environmental commodity for which there is market price. Altogether, the reserves module includes eight different types of reserves (subscript s): coal, petroleum, natural gas, fish, timber, $CaCO_3$ minerals, PO_4^{3-} minerals, and S minerals. An overview causal loop diagram for the reserves module and its connection to the wider Ecocycle model is provided in Figure 9.3, with the full Vensim® influence diagram and equations for the reserves module available in Section G.5 of Appendix G.

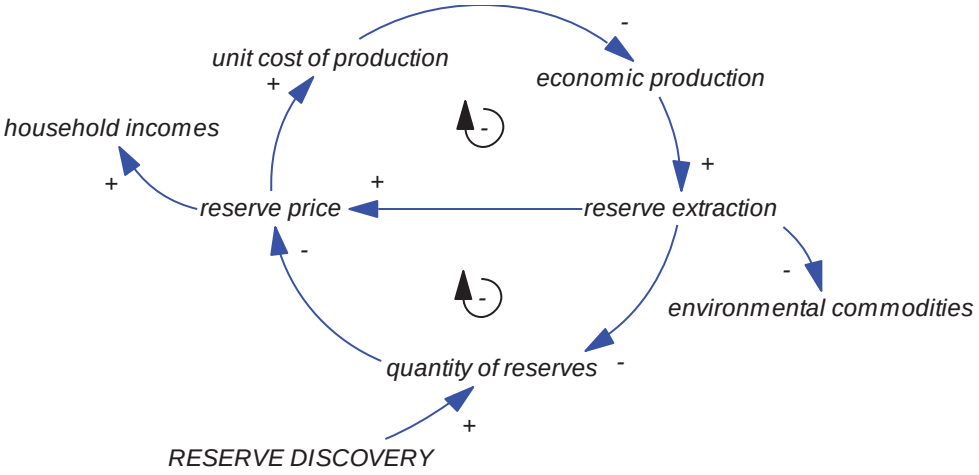

Figure 9.3 Incorporation of Environmental Reserves within Ecocycle: Overview

In short, the purpose of the reserves module is to track changes in the price of commodity reserves. These prices then become an important input to the economic components of the model by way of modification to the unit cost of production for industries. Thus, Eq. 7.26 within the original DGES model is substituted for Eq. 9.2 below. The stock $Preserv_s$ defines the price for reserve s, while $AN_{j,s}$ is the (Leontief) input coefficient for reserve s within industry j.[189] The constant $ONATRES_j$ is further added to the unit cost equation, to allow for any non C, N, P, or S reserves (e.g. metal minerals) to also be included in the calculation of industry unit production costs.

[189] The $AN_{j,s}$ coefficients are populated by data from the GTAP 7.0 database, where quantities of reserves used by industries are recorded in monetary units. However, the reserve prices, $Preserv_s$, are recorded in monetary units per *mass* of reserve. The constant $PRESERVBASE_s$ is applied to convert the prices into monetary units per quantity of reserve, with quantities measured in monetary units.

$$unitcostprod_j = factinputshare_j \times Pcfact_j + \sum_{i*}\left(interinputshare_{i*,j} \times pcomdshort_{i*,j}\right) + \sum_s\left(AN_{j,s} \times Preserv_s \times \frac{1}{PRESERVBASE_s}\right) + ONATRES_j \quad . \quad (9.2)$$

Similar to the way in which other prices are determined within the model, reserve prices change over time in response to changes in the size or supply of reserves, relative to their rate of removal by industries.[190] The quantities of reserves removed by industries are calculated simply by multiplying the value of production for each *j* industry, by the relevant $AN_{j,s}$ coefficients.[191]

In terms of reserves supply we can note that, at least in the context of fossil fuels and minerals, commodity *reserves* are normally distinguished from commodity *resources* and *geopotential* (see, for example, Wellmer (2008)). The general idea is that while resources include all known stocks of a commodity (to various levels of certainty), reserves are only the share of resources that can be economically extracted under current market conditions and technologies. Geopotentials cover all reserves and resources of the future, but are unknown at present. Despite the boundaries between reserves and resources and between resources and geopotentials clearly changing over time, many of the mathematical models put forward to describe the economic supply of environmental commodities employ a static view of reserves and/or resources, including the so-called 'Hubbert curve' models. This has led to a call for significant further development in models that are *dynamic*, allowing for both changes in the potentials of *reserves* and *resources*, as well changes in demand for these commodities (Scholz and Wellmer, 2013).

While research into the system relationships underpinning changes in reserves would be an interesting and worthwhile subject of future enquiry, for the time being the inclusion of such dynamics is beyond the scope of the model. Thus, annual additions to Ecocycle's lithosphere reserve stocks are simply set according to an exogenous, i.e. scenario-derived, value.[192]

[190] See Eqs. G.73–G.78.
[191] See Eq. G.79.
[192] See Eq. G.81.

9.3.2 Resources and Residuals Module

The resources and residuals module essentially tracks the flow of materials from the environment to the economy, and vice versa. To assist readers in interpreting the way in which these mass flows are determined within Ecocycle, a summary causal loop diagram is depicted in Figure 9.4. A more detailed explanation, including a Vensim® influence diagram and equations follows.

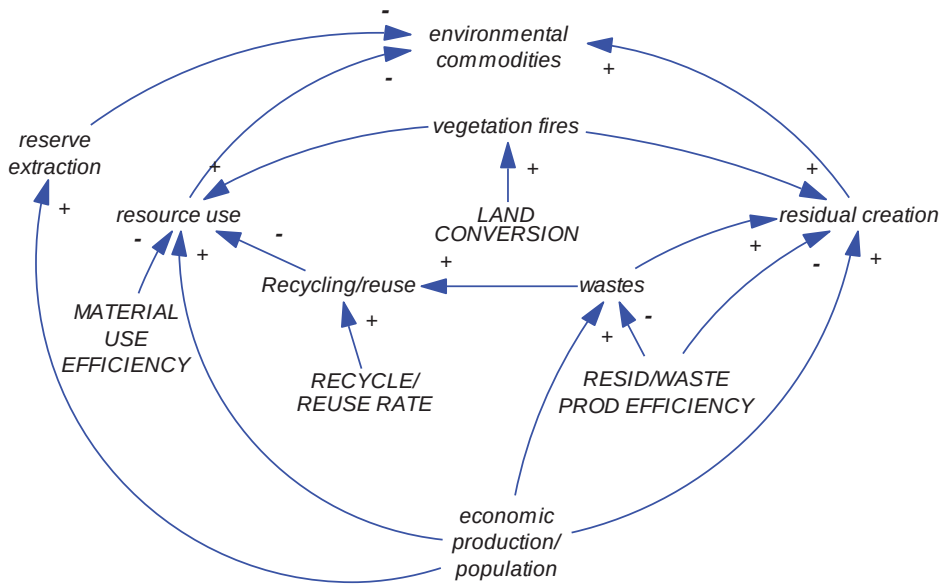

Figure 9.4 Incorporation of Resources and Residuals within Ecocycle: Overview

Figure 9.5 depicts the flow of C into and out of the Anthrosphere.[193] As the equations used within the module follow the same structure for each of the C, N, P, and S cycles, this section concentrates on describing only the C-related components.[194] On the input side, the flow *cresourceuse* represents the total quantity of C 'extracted' from the environment according to all the direct material input and non-processed material flow categories described in Chapter 4.[195] These flows, in turn, are separated into three categories, *creserveextract*, *cfires*, and *cotherusenet*.[196] The first category covers all C inputs associated with the extraction of reserves, as calculated under the reserves module.[197] Changes in stocks resulting from human-

[193] See Eq. G.82.
[194] Full equations for the resources and residuals module are available in Section G.6 of Appendix G.
[195] See Eq. G.85.
[196] See Eq. G.84.
[197] See Eq. G.86.

induced fires, $cfires$, are also given special consideration on the basis that these flows will be correlated with the rate of land conversion;[198] an input also to the capital module.

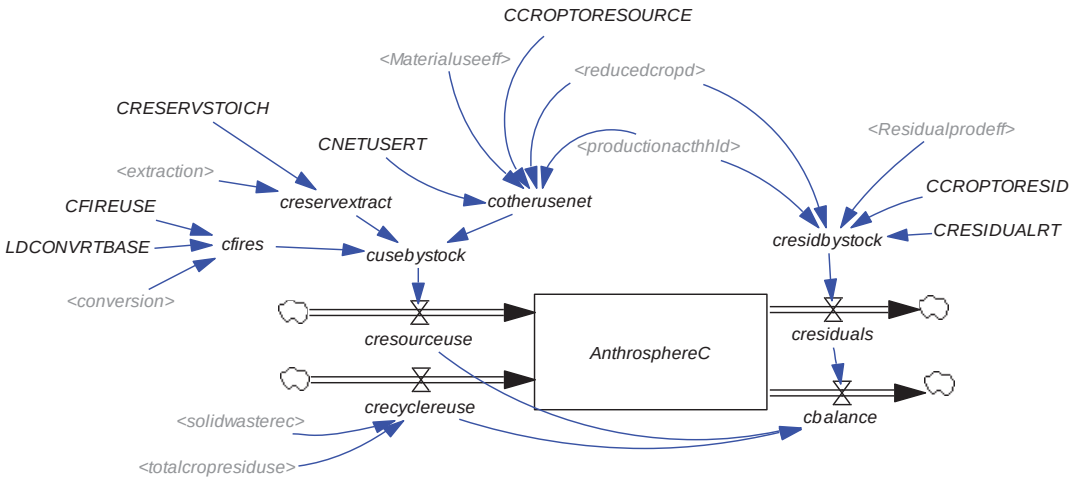

Figure 9.5 Anthrosphere Carbon Influence Diagram

All other types of direct material inputs and non-processed material flows are grouped within the *cotherusenet* converter. For the most part these flows are derived simply by using a set of coefficients from the base year data, $CNETUSERT_{\gamma,m^C}$, describing the net use of environmental commodity m^C, per unit of production within sector γ.[199,200] The module allows, however, for possible increases in material use efficiency, brought about by an exogenous rate of efficiency increase, $MATEFFGRRT\gamma$.[201] Furthermore, the module also allows for changes in material efficiency brought about by increased use of crop residuals.[202] The total share of crop residuals used by the economy is an exogenous constant that can be adjusted under different scenarios.[203] Any increase in crop residual use is assumed to reduce the demand that would otherwise be required for biomass directly from crops, although there is an allowance for possible variations in biomass quality.

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[198] See Eq. G.85.
[199] In the case of the households sector, which is not responsible for economic production, total change in population compared with the base year population determines the rate of resource use, rather than change in production (see Eq. G.146).
[200] Note also that, since the $CNETUSERT$ coefficients include all non-processed material flows, some flows are *to* stocks rather than *from* stocks (i.e. negative net resource use).
[201] See Eqs. G.147–G.148.
[202] See Eq. G.87.
[203] See Eqs. G.122–G.128.

On the output side, the flow *cresiduals* captures C flows out of the economy via the production of residuals and wastes.[204] These flows are also separated into individual receiving stocks under the $cresidbystock_{\omega^C}$ converter. The subscript ω^C is used, rather than m^C, as the receiving stocks include not only environmental commodities, but also the landfill, crop residuals, and solid waste stocks. The quantities of C emitted in these flows are determined simply from sector-specific coefficients, $CRESIDUALRT_{\gamma,\omega^C}$, stipulating the mass of commodity ω^C produced, per unit of economic production.[205] Furthermore, there is an allowance for increases in the efficiency of residual/waste production, brought about through an exogenous efficiency growth rate, $RESIDEFFGRRT\gamma$.[206] The model additionally captures changes in the quantities of crop residuals produced, through increased economic use of these materials.[207]

Returning to the input side, the flow *crecyclereuse* is the sum of all C contained within used crop residuals and recycled solid wastes.[208] Similar to the treatment of crop residuals, the model contains an exogenous rate of recycling for solid wastes that can be altered under different scenarios.[209] Stocks of both crop residuals and solid wastes not used by economic activities are released into the environment through waste treatment processes. In both cases, it is assumed that the share of environmental commodities produced during waste treatment remains consistent with the base year data from Chapter 4.[210] Note that a proportion of decomposable organic C waste deposited within landfills is released into the atmosphere via a constant emission rate, thereby producing a flow of emissions, *lfemissions*.[211] However, no attempt has been made to account for other types of matter flows out of landfill sites.

The final C flow out of the Anthrosphere is termed *cbalance*. It is calculated by simply summing together C flows into the economy contained in *cresourceuse* and *crecyclereuse*, and then subtracting C flows contained in *cresiduals*.[212] As already explained in Chapter 7, further

[204] See Eq. G.90.
[205] Again the coefficients for the household sector are set relative to population rather than economic production.
[206] See Eqs. G.149–G.150.
[207] See Eq. G.89.
[208] See Eq. G.88.
[209] See Eqs G.134–G.137.
[210] See Eqs. G.129–G.130, G.138–G.139.
[211] See Eqs. G.143–G.145.
[212] See Eq. G.91.

research will help refine the residual and waste production accounts, and by corollary, improve estimates of matter accumulation within the economy. For the time being, it is simply assumed that all balance C is released relatively quickly into the environment, either directly or indirectly as atmospheric C.[213]

Connecting the physical flows into and out of the Anthrosphere with the environmental commodity stocks contained in the original BGCM model enables the full implications of human resource use and residual creation on biogeochemical cycling to be captured. The integration occurs simply by adding together all of the anthropogenic physical flows associated with resource use and residual creation to create a net C use flow for each environmental commodity stock, $cnetuse_{m^C}$.[214] These flows are then added to the appropriate equations responsible for calculating the environmental commodity stocks. For example, the stock of C in vegetation/zoomass is now defined by the equation,

$$VegezoomasC(t+1) = VegezoomasC(t) + \begin{pmatrix} anth5C + tnpp1C - ctmo1C - czpr1C \\ -wfve1C - wfve2C - wfve3C \end{pmatrix} \times dt,$$

where $anth5C$ is the net anthropogenic use of vegetation/zoomass. Thus,

$$anth5C = -cnetuse_{\text{VegezoomasC}}.$$

9.3.3 Other Components of the Ecocycle Model

This section describes three further extensions to the original DGES and DGBCM models incorporated within the Ecocycle Model.

Cropland Efficiency of Net Primary Production

As explained in Section 9.3.2, the Ecocycle model includes an exogenous parameter $MATEFFGRRT$ that enables users to investigate scenarios involving improvements in the material input efficiency of production. In the agricultural crops industry this might involve, for example, the introduction of crops exhibiting less residual production, thereby reducing the quantities of inputs required by the crop industry, per unit of economic production. To ensure

[213] The stocks allocated balance flows under the N, P and S cycles are, respectively, DetritusN, DetritusP and DetritusS.
[214] See Eq. G.157.

that such efficiency changes are taken into account when calculating the land requirements of the industry, the stock *Croplandinputeff* is introduced, and forms an input to the capital module.[215]

Accounting for Crop Production in the Calculation of Global Terrestrial NPP

Consistent with the approach taken in Chapters 3–5, the process of terrestrial NPP is defined as occurring partly within the agricultural crop industry. Thus when calculating the flow of materials between ecological stocks associated with terrestrial NPP, it is important to account for the proportion of NPP already included in the anthropogenic material flows as outlined in Section 9.3.2. This is achieved through modification of the formula deriving the flow rate for terrestrial NPP, $fluxrate_{tnpp}$.[216]

Input Efficiencies for Intermediate Consumption

Most economic (CGE) models employ constant technical coefficients for intermediate inputs within the production functions of industries. This is a pragmatic approach to deal with the complexity that would otherwise be involved in attempting to model the numerous input substitution possibilities of multiple industries. The DGES model also employs constant (Leontief) technical coefficients for these reasons. Nevertheless, it is been found that when multiple industries are defined within the model, constant input coefficients can lead to instability, especially when the model is run over a long period (i.e. more than 50 years). On reflection, this is an appropriate outcome: if a particular input is in short supply relative to other inputs, and thus its price starts to rise at a greater rate than other inputs, instability will result unless there are feedback structures that help to regulate the use of that input in relation to other inputs.

Although full modelling of technical change (including substitution between intermediate inputs) is beyond the scope of this thesis, it is nevertheless considered appropriate to allow for some minor alterations to the efficiency of inputs to production, to reflect price changes responses and enhance the stability of the economic components of the model. This is achieved through incorporation of a lookup function that results in a minor adjustment to the input coefficient of a commodity, when the price of that commodity varies significantly from the average price of intermediate inputs for the relevant industry.[217]

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[215] See Eqs. G.151–G.154, G.48.
[216] See Eqs. G.155–G.154.
[217] See Eqs. G.31–G.34.

9.4 Setting of Model Parameters

Before illustrating the operation of the model though the use of test scenarios, it is necessary to outline some of the default parameters incorporated within the model for its initial trial runs. Dealing first with the biophysical components of the model, all input variables required for the modelling of 'within-environment' biogeochemical flows (i.e. base year stock values, flow element ratios, SNK and K constants) are the same as set out in Chapter 8. Next, the input variables required for the resources and residuals module are derived almost entirely from the material flow accounts contained in Chapter 4 of this thesis. Like in Chapter 7, the GTAP 7.0 database is relied on to derive the initial conditions for the economic components of the model via aggregation of the 113 individual regional SAMs contained within the database into a single world SAM. To reduce the complexity of the model, the 57 sectoral definitions contained within the GTAP database are also aggregated to form 17 unique commodity/industry types (refer to the concordance in Appendix C).

The various parameters required for the CES/CET functions are derived by first setting elasticity values based on ranges given within the literature, and then calculating share and scale parameters through a calibration processes assuming that the model is in equilibrium at the base year. Elasticities for factor substitution (i.e. between labour and capital) range from 0.2 to 1.26, and are taken directly from the base elasticities used in the GTAP CGE model. Similarly, the elasticity of substitution between land and other forms of capital within the crops (CropsA) and animals and unprocessed animal products (AnimsA) industries are set respectively as 0.24 and 0.23, based on the GTAP input parameters.

Ahmed *et al.* (2008) investigated the elasticity of land supply across different uses, also for the purpose of GTAP CGE modelling. A value of 0.6 for the elasticity of transformation between cropland and grazing land is selected based on this work. Furthermore, applying the same parameter as adopted by Birur *et al*. (2008), the elasticity of transformation between crops is set as 0.5. Unfortunately, the investigation of appropriate elasticity values between intermediate goods and factors is relatively poorly documented in the literature and thus for now the elasticity value for all industries is set low at 0.3. Additionally, for the initial trial runs of the Ecocycle model, only one type of labour skill is considered, meaning that the elasticity of transformation in the supply of labour skills is irrelevant. Lastly for the energy module, and

informed by the work of Kemfert and Welsch (2000), the elasticity of substitution between electricity and composite fuels is set as 0.6, while the elasticity for fuels is set at 0.8.

9.5 Scenario Analysis

Scenario modelling is one approach that may be employed to simulate possible futures associated with human perturbation of the biogeochemical cycles (Wilson, 1978; Schwarz, 1991). While it is impossible for us to predict the future it is, however, useful to gain insight into plausible development trajectories, thus reducing uncertainty and avoiding risk. The 'art and science' of scenario development has not been addressed in this thesis as third party scenarios have been applied. Nevertheless, there are several reasons why further scenario analysis is required: (1) it helps identify omissions, gaps, and inconsistencies and highlights opportunities for further development; (2) it is arguably the only approach suitable for long-run analysis with highly uncertain dynamic systems; and (3) it may provide common ground for communicating findings with other researchers.

Authors such as Wilson (1978), Linneman and Klein (1979), van der Heijden (1996), and Ringland (2006) fully outline the scenario development process. This often involves: (1) selection of scenario themes – requires consideration of cause and effect, internal consistency, relevance to key issues, and avoidance of contradictory sub-themes; (2) careful detailed, plausible and informative storylines – formulated as a qualitative narrative with clearly documented assumptions; (3) setting of initial conditions; (4) establishment of key indicators; (5) simulation; and (6) reporting – comparison of scenario is critical as it provides insights into strengths, weaknesses, and trade-offs. Importantly, the scenario development process is iterative, often with many rounds. Although the number of imaginable scenarios is infinite, scenarios are most powerful when presented as a small set with marked differences (van der Heijden, 1996).

9.5.1 The Millennium Ecosystem Assessment Scenarios

Thus far, Ecocycle has been tested through the application of two trail scenarios, both taken from the Millennium Ecosystem Assessment (MEA, 2005). Although these scenarios extend for a period of 100 years, only the period of 30 years starting at the model base year of 2004 is considered.[217a]

The MA Scenarios Working Group sought to examine possible changes in ecosystem services during the 21st Century by putting forward four global scenarios, each of which explore possible future changes in drivers, ecosystems and ecosystem services, and human wellbeing. Although published in 2005, the work is still among the most comprehensive and relevant examples of scenario development with regards to the types of issues considered in this thesis. The four scenarios are distinguished principally by their placement within two spectrums: the first describes the tendency toward either stronger globalization or stronger regionalization, and the second describes their emphasis on either economic growth or proactive management of ecosystems and their services (Alcamo *et al*., 2005a).

Two of these MA scenarios are selected for application within Ecocycle, namely the Global Orchestration and TechnoGarden scenarios. The Global Orchestration scenario envisages a "[g]lobally connected society that focuses on global trade and economic liberalization". It also "[t]akes a reactive approach to ecosystem problems, but also takes strong steps to reduce poverty and inequity and to invest in public goods, such as infrastructure and education" (Alcamo *et al*., 2005b, p.3). The TechnoGarden scenario also envisages a globally connected world but it relies "strongly on environmentally sound technology. This world uses highly managed, often engineered, ecosystems to deliver ecosystem services, and takes a proactive approach to the management of ecosystems in an effort to avoid problems" (Alcamo *et al*., 2005b, p.3). Although population growth is a higher under the TechnoGarden scenario than the Global Orchestration scenario, the former generally performs best in terms of the environmental indicators reported by the MA, including greenhouse gas and nitrogen oxides emissions, seal-level rise, and deforestation.

Table 9.1 Key Inputs for the Global Orchestration and TechnoGarden Scenarios

	Global Orchestration			TechnoGarden		
	2004-2014	2014-2024	2024-2034	2004-2014	2014-2024	2024-2034
Population (annual average growth)						
Total population	0.9%	0.7%	0.4%	1.1%	0.9%	0.6%
Labour force	1.7%	0.7%	0.3%	1.9%	0.9%	0.4%
Factor productivity (annual average growth) [1]						
Labour	2.4%	2.7%	3.0%	2.7%	2.9%	3.2%
Capital - Crops, Forst,Wdpap	2.4%	2.7%	3.0%	2.3%	2.5%	2.6%
Capital - Anims	3.1%	3.5%	4.0%	2.7%	2.9%	3.2%
Capital - Other ind.	2.4%	2.7%	3.0%	2.0%	2.3%	2.4%
Agricultural land (10^9 m^2)						
Net increase	620	260	730	370	100	720
Reserves (annual average gross additions)						
Coal (Pg C)	7.34	6.09	5.59	2.12	1.38	1.06
Petroleum (Pg C)	5.19	5.19	5.19	2.43	2.01	1.84
Gas (Pg C)	3.75	3.90	4.03	2.59	2.48	1.21
Calcium carbonate (Pg C)	0.37	0.49	0.49	0.34	0.38	0.35
Phosphate (Tg P)	24	31	31	22	24	22
Sulphur (Tg S)	37	49	49	34	38	34
Production tax rates (annual average growth)						
Coal, Oil, Gas	7.2%	4.1%	2.9%	14.3%	1.8%	0.9%
Other commodities	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Industry input coefficients (average annual change) [1,2]						
Crops,Anims	0.2%	0.0%	0.0%	2.4%	1.9%	1.6%
Crops,Fofib	0.0%	0.0%	0.0%	0.7%	0.5%	0.6%
Crops,Wdpap	0.6%	0.6%	0.6%	0.7%	0.5%	0.6%
Crops,Const	0.7%	0.6%	0.6%	0.7%	0.6%	0.6%
Anims,Fofib	-0.3%	-0.4%	-0.4%	-1.8%	-2.1%	-2.9%
Forst,Wdpap	-2.8%	0.0%	0.0%	-2.8%	0.0%	0.0%
Forst,Const	-2.8%	0.0%	0.0%	-2.8%	0.0%	0.0%
Chmin,Crops	-0.1%	-0.1%	-0.1%	-0.2%	-0.3%	-0.2%
Chmin,Anims	-0.1%	-0.1%	-0.1%	-0.2%	-0.3%	-0.2%
Energ,Elect	-0.2%	-0.1%	0.0%	-0.1%	-0.7%	-1.0%
Energ, All ind. (excl Elect)	-0.5%	-0.7%	-0.3%	-0.4%	-0.4%	-0.3%
All com. (excl Energ),Elect	1.8%	0.1%	0.0%	2.3%	0.7%	0.9%
All other combinations	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Notes: 1. Anims = animals and unprocessed animal products (ind. or com.), Forst = Forestry (ind. or com.) Fofib = food and fibre products (ind. or com.), Wdpap = wood and paper products (ind. or com.), Chemin = chemical and mineral manufacturing (ind. or com.), Elect = electricity ind., Energ = energy commodity. 2. Denotes the quantity of a commodity (left-hand side) utilised by an industry (right-hand-side) per unit of production by the industry.

As the quantitative aspects of the scenarios were generated though application of a separate set of global simulation models differing in structure to Ecotime, no attempt has been made to

ensure that Ecotime exactly conforms to the variables reported for each of the scenarios. Instead, for each scenario, the various economic parameters within Ecotime are adjusted to ensure that overall the input and output variables are generally consistent with those reported by the Millennium Ecosystem Assessment. Key input variables for each of the scenarios are summarised in Table 9.1.

Population growth under the Global Orchestration scenario is underpinned by low fertility and low mortality assumptions, while for the TechnoGarden scenario, medium fertility and a medium pace of mortality change are assumed. The adopted rates of growth in factor productivity are among the most important variables in determining the level of economic growth. Over the last 110 years, global GDP has increased at a rate of about 2.7 percent per year, or 1.5 per cent per year when measured in per capita terms (Maddison, 1995). Under the Global Orchestration scenario, economic growth is assumed to be above historic averages in a number of world regions due to trade liberalisation, economic cooperation, and rapid spread of new technologies (Alcamo *et al*., 2005a). Productivity and economic growth is generally lower under the TechnoGarden scenario, at least for the 30-year timeframe considered. Note that under both scenarios, capital productivity growth is set highest for the industry producing animals and unprocessed animal products. This reflects significant increases in farming intensity, and thus outputs per hectare of farmed land. Nevertheless, these efficiency gains with respect to land must be supported by increases in the quantities of crop feed purchased by this industry.

Under the Technogarden scenario, the international community supports long-term reductions of greenhouse and other air pollutant emissions (Alcamo *et al*., 2005a). Thus, the production tax rates for coal, oil, and gas are set to increase very significantly under the TechnoGarden scenario. This helps push energy demand towards non-fossil sources. Overall, the expansion of agriculture land is relatively similar under the two scenarios despite some variations in the underlying driving forces. Although population growth is comparatively low for the Global Orchestration scenario, high economic growth helps raise the calorific diet of the world's population. Increasing energy demands are also met partly by growth in biofuel crops. Under the TechnoGarden scenario, population growth is higher but calorific intake per capital (particularly meat consumption) is lower, and thus increases in crop yield generally balance additional food requirements. Nevertheless, there are also relatively significant increases in agricultural land for biofuel production under this scenario.

9.5.2 Scenarios Results

To start the results section, Figure 9.6 provides results for two commonly utilised economic variables: total economic output and GDP per capita. Total economic output is the sum of all commodities produced by economic industries, valued in 2004 terms. Under the TechnoGarden scenario, growth in service commodities is especially high (3.5 percent per annum), driven particularly by falling relative prices for services, and high growth in household consumption. The declining price for this commodity, relative to other commodities, is attributable partly to comparatively low direct and indirect demands for scarce environmental resources, including energy, in production. The electricity commodity also experiences strong growth under the TechnoGarden scenario (2.5 percent per annum), reflecting its increasing market share of energy demand. In addition to strong growth in the production of services and electricity (4.0 and 3.7 percent respectively), the Global Orchestration scenario exhibits strong growth in output of agricultural and forestry commodities (around 2.5 percent per annum).

The average growth rate in GDP per capita under the Global Orchestration scenario is nearly double the historic rate descried above, at 2.9 percent per annum. Even under the TechnoGarden scenario, the growth rate in GDP per capita is reasonably high at 2.0 percent per annum.

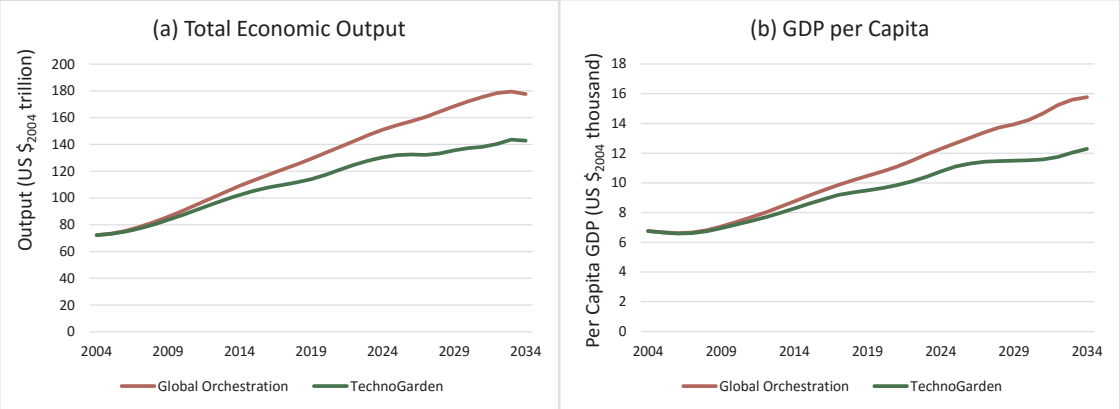

Figure 9.6 Total Economic Output and GDP per Capita under the Global Orchestration and TechnoGarden Scenarios, 2004-34

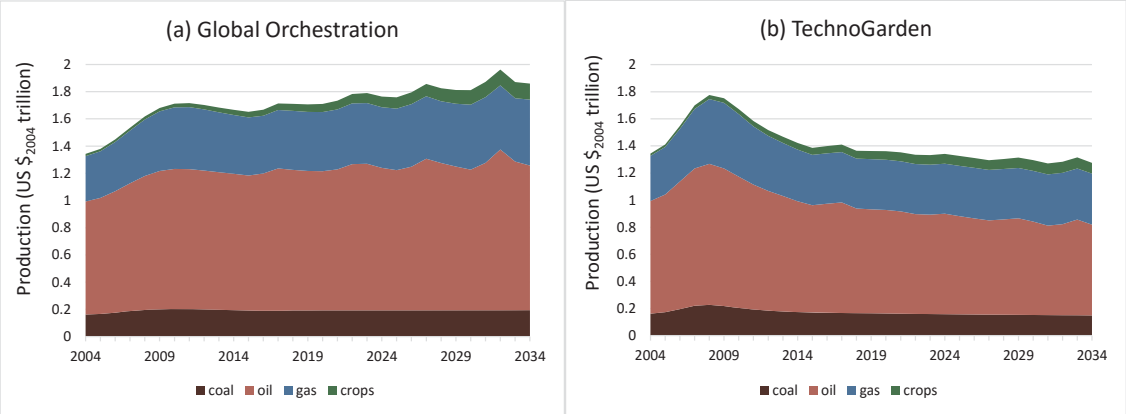

Figure 9.7 **Production of Energy Commodities under the Global Orchestration and TechnoGarden Scenarios, 2004–34**

The dynamics of energy consumption and production are quite different under the two scenarios (Figure 9.7). Initially, growth in petroleum production is relatively high for the TechnoGarden scenario. However, after around 5 years, production starts to subside in response to depleting reserves, ongoing improvements in energy efficiency and increasing availability of alternative energy options. The TechnoGarden scenario is thus characterised by a very clear 'peak oil' trend. Although both scenarios show a marked increase in the production of biofuel crops compared with the base year (a staggering 6.7 percent per annum growth for Global Orchestration and 5.3 percent for Technogarden), total biofuel crop energy is still relatively small when compared with conventional fossil fuels. Under the Global Orchestration scenario, the annual addition to oil reserves is set at a constant rate of 5.2 Pg C. This goes against the historic trend in annual reserve discovery, which has shown marked decline over time (Sorrell *et al.*, 2010) and thus likely implies strong reliance on non-conventional oil resources. Nevertheless, towards the end of the study period, constraints on oil reserves start to place significant stress on the economic system, evidenced by growing fluctuations in oil prices and in the production of the commodity.

Changes in C, N, P, and S stocks under the two scenarios are depicted in Figures 9.8-9.11. Note that annual flows are often quite small in comparison with the magnitude of global stocks. Thus, in order to enable the changes over time and between scenarios to be visible, the y-axis scale varies among the diagrams.

The atmosphere stocks show some of the most significant changes over the 30 years considered. Atmospheric reactive N, in particular, increases by around 31 percent under the Global Orchestration scenario, and 21 percent under the TechnoGarden scenario. More than

half the total reactive N emitted by the economy under the Global Orchestration scenario originates from the two agricultural industries. The situation is also similar under the TechnoGarden scenario, despite quite substantial reductions in nitrogen fertiliser inputs to agriculture (Table 9.1). It is noted that although atmospheric C also increases quite substantially under the two scenarios, particularly the Global Orchestration scenario, these changes would appear to be less pronounced than the changes anticipated under the IPCC scenarios (Friedlingstein *et al*., 2006). This is primarily because, as discussed in Section 8.5, the environmental components of Ecotime model are donor stock driven, and thus do not consider ocean acidification and other dynamics that start to limit the rates at which the oceans can take up atmospheric C as the mass of ocean C increases. Nevertheless, considering both atmospheric C and ocean C together, the Ecotime model clearly demonstrates strong growth in C within the reactive (i.e. non-lithosphere) biosphere stocks. Interestingly under both scenarios considered, atmospheric S actually reaches a peak level and then starts to decline, with the peak more pronounced and earlier under the TechnoGarden scenario. This largely reflects the peak in demand for coal and oil, as combustion of these fuels is the major source of anthropogenic atmospheric S emissions.

Despite quite significant increases in reactive soil N under the two scenarios (Figure 9.9), element stocks within vegetation fall by around 4 percent under the Global Orchestration scenario and 3 percent under the TechnoGarden scenario. Recall that Ecotime does not contain separate freshwater stocks and a significant proportion of soil N is likely to be unavailable to terrestrial vegetation. Also land available for terrestrial vegetation is progressively appropriated under both scenarios for agricultural production (Table 9.1). Furthermore, under both the Global Orchestration and TechnoGarden scenarios, the quantity of terrestrial vegetation removed by the global economy increases, from around 8 percent of annual NPP at the base year, to around 13 percent in 2034.

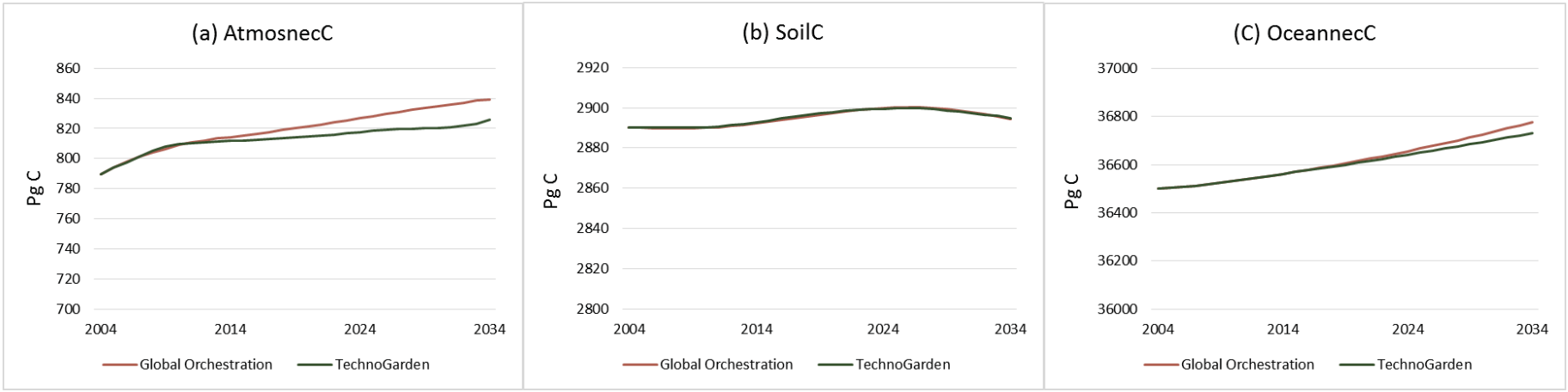

Figure 9.8 **Selected Global Carbon Stocks Under the Global Orchestration and TechnoGarden Scenarios, 2004-34**

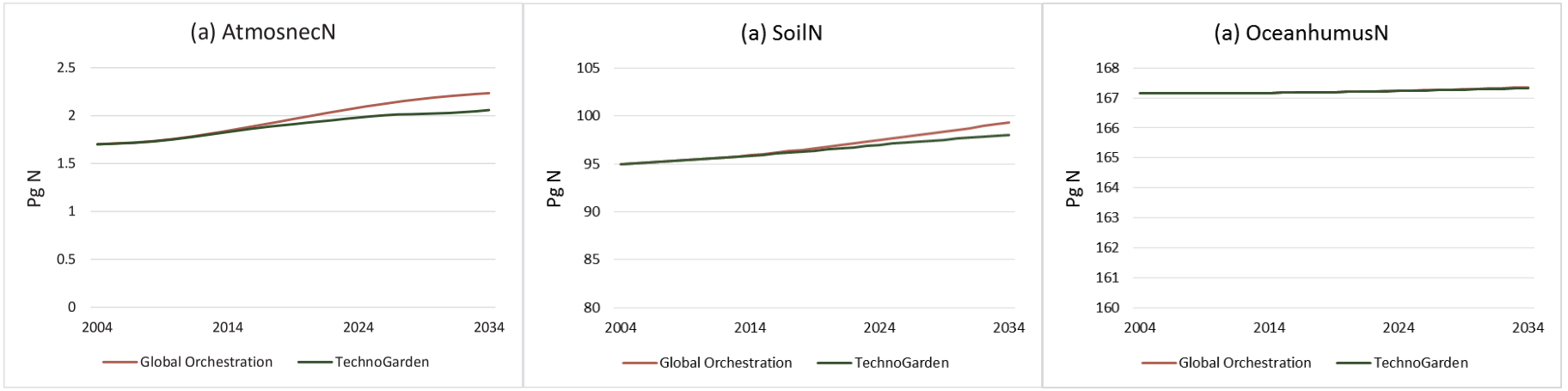

Figure 9.9 **Selected Global Nitrogen Stocks Under the Global Orchestration and TechnoGarden Scenarios, 2004-34**

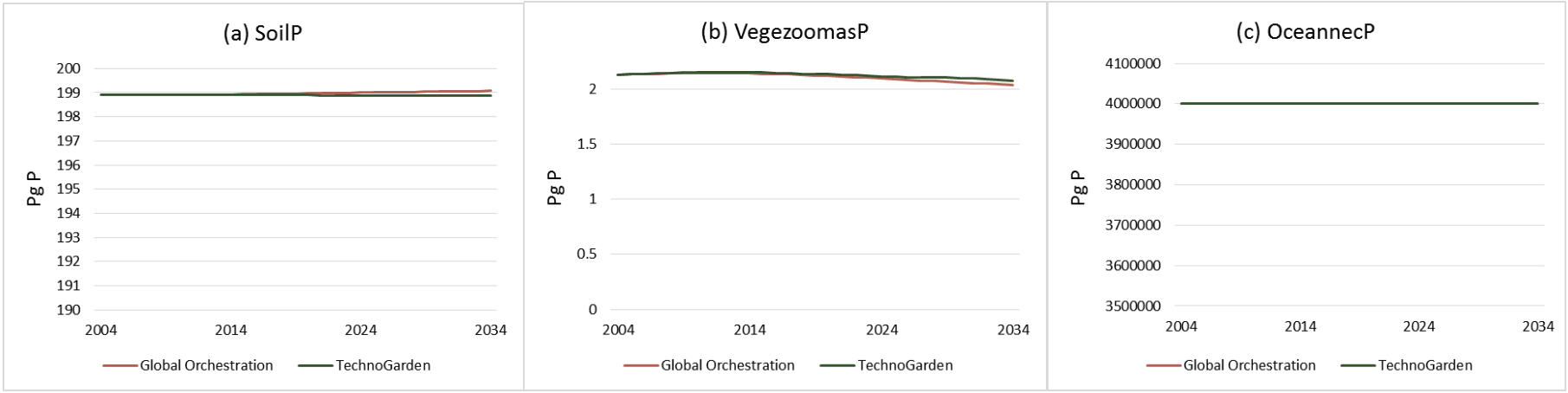

Figure 9.10 Selected Global Phosphorus Stocks Under the Global Orchestration and TechnoGarden Scenarios, 2004-34

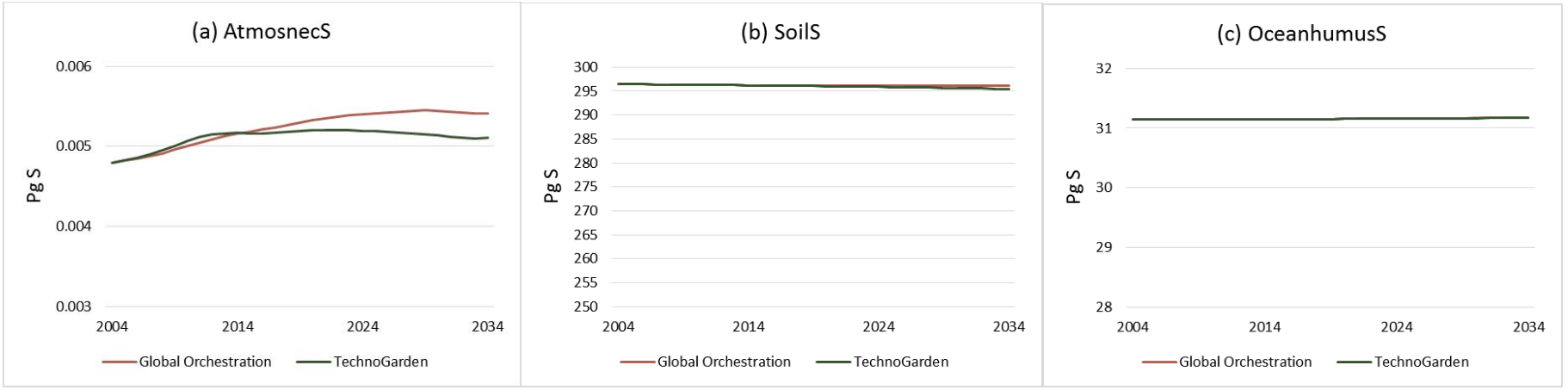

Figure 9.11 Selected Global Sulphur Stocks Under the Global Orchestration and TechnoGarden Scenarios, 2004-34

Figures 9.12–9.15 present the calculated Ecological Overshoot at 10-year intervals, for selected biogeochemical processes, based on the Ecotime concept as set out in Chapter 6. Note that the Ecocycle model contains fewer stocks and processes than those considered in Chapter 6. Thus to ensure consistency with the earlier chapter, it has been necessary to disaggregate data extracted from Ecocyle before calculation of the Ecotime indicators. For this reason, the results given in Figures 9.12–9.15 are indicative only. Another point of difference from the analysis described in Chapter 6 is that for each element within Ecocycle, any net changes between resource use and residual generation is assigned as a residual flow to a selected environmental stock (see Section 9.3.2). For this reason the base year estimates of Ecological Overshoot are a little higher than those reported in Chapter 6.

Generally speaking, under the Global Orchestration scenario the increase in Ecological Overshoot for key biogeochemical processes is very high, even to the point of alarming. For the C processes covered by Figure 9.12, Ecological Overshoot increases between 22 and 56 percent within a period of just 30 years. Similarly, growth in Ecological Overshoot for N processes in Figure 9.13 ranges between 27 and 49 percent over the study period. Interestingly, the growth in Ecological Overshoot for P processes is even higher – ranging between 49 and 81 percent for the processes covered by Figure 9.14. As in the case of the N cycle, the P cycle is subject to increasing stress due, in particular, to growing demand for agricultural fertilisers. Only to a small extent does the N cycle adapt to increasing introduction of reactive N, by increasing rates of natural denitrification. In the case of the P cycle, natural responses are even less significant at balancing the additional introduction of nutrients, as the only non-negligible processes for removal of reactive P is by way of deposition within marine sediments: a process which is small in scale and slow to adjust.[217b] In the case of the S cycle the results are slightly more positive, with the Ecological overshoot of the process of sulphate deposition falling by 2 percent over the study period, largely reflecting substitution away from coal combustion in energy production.

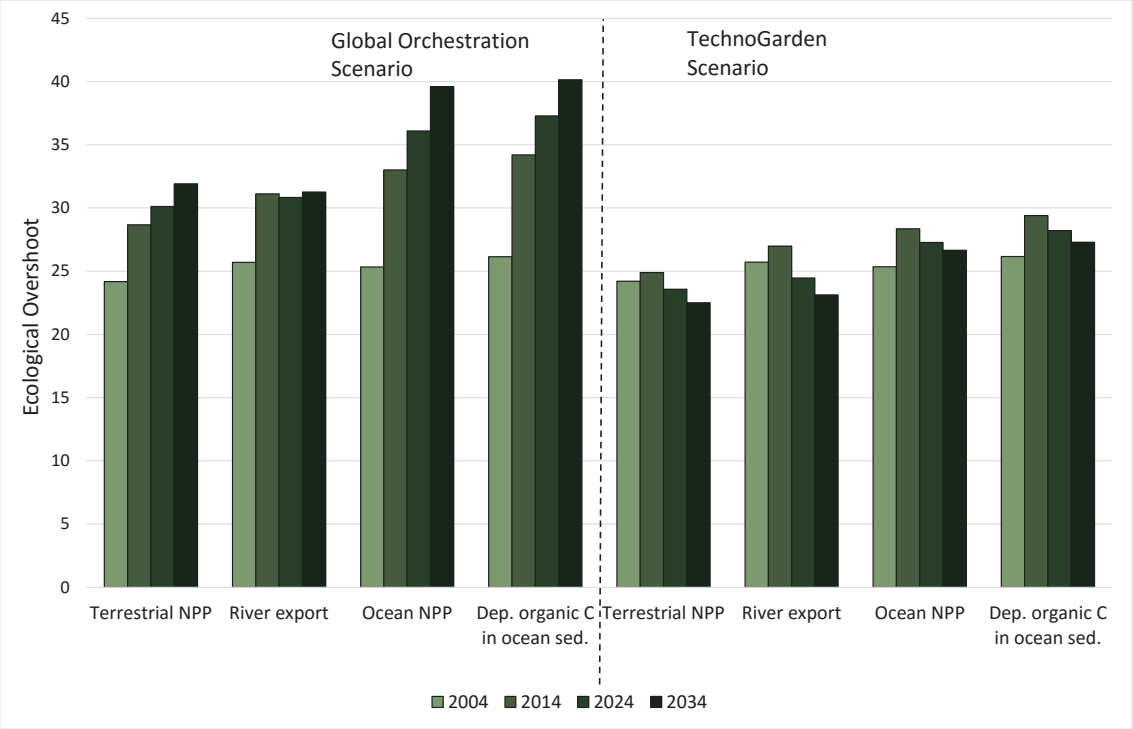

Figure 9.12 Ecological Overshoot for Selected C Processes, 2004–34

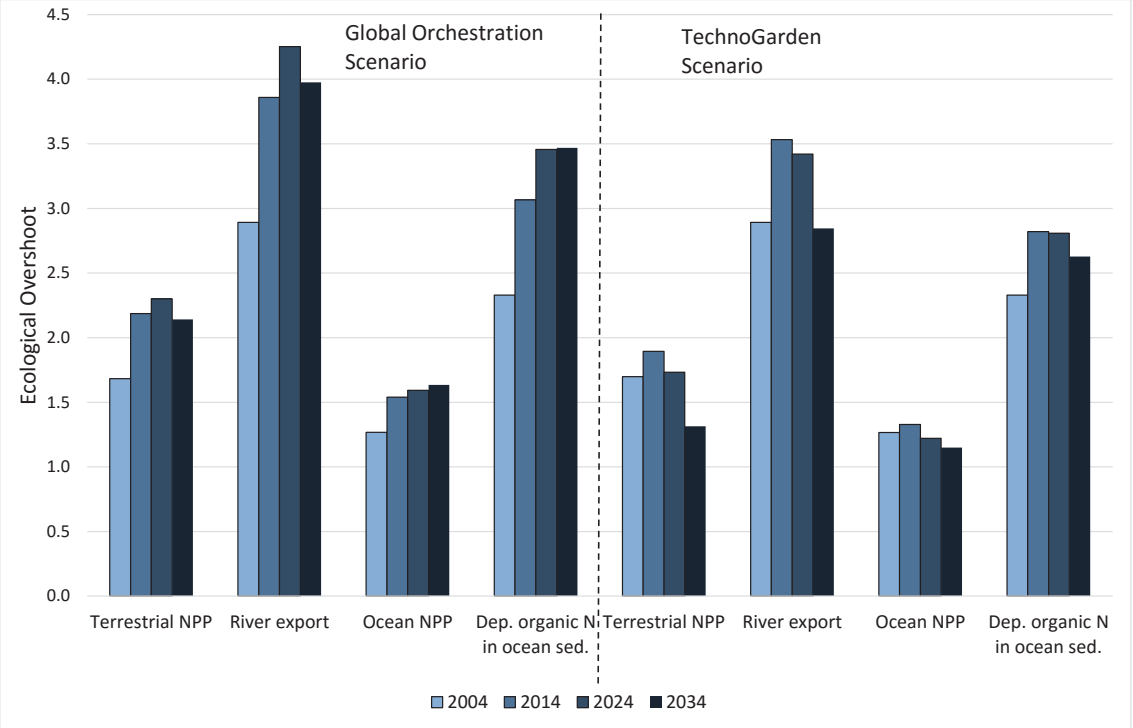

Figure 9.13 Ecological Overshoot for Selected N Processes, 2004–34

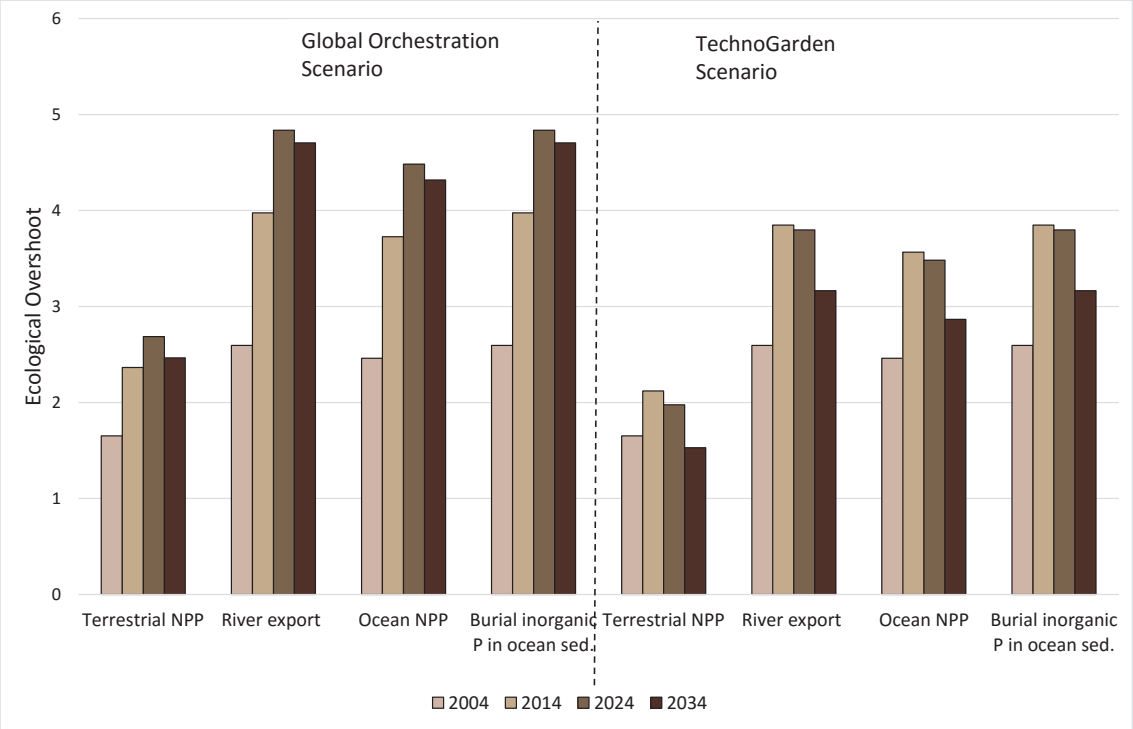

Figure 9.14 Ecological Overshoot for Selected P Processes, 2004–34

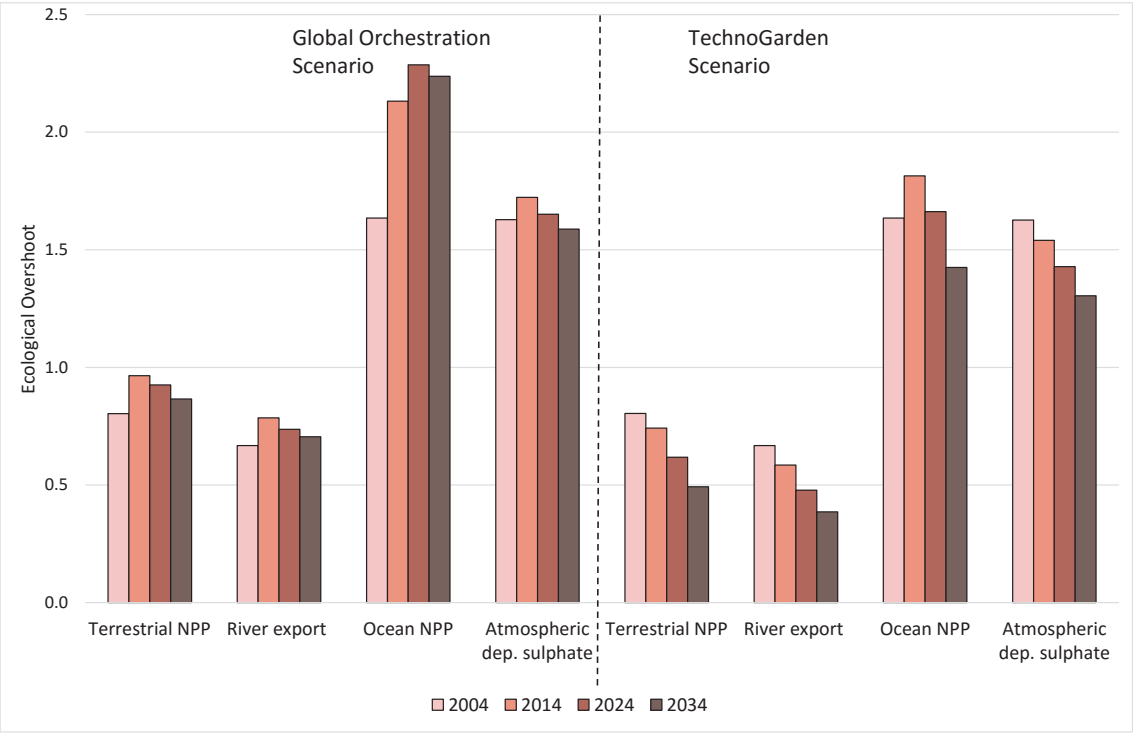

Figure 9.15 Ecological Overshoot for Selected S Processes, 2004–34

Even under the TechnoGarden scenario, which is generally the most optimistic of the MA scenarios in terms of reported environmental indicators, the extent of overshoot of C cycle processes is set to remain relatively constant to the base year. Initially, overshoot for each of the N and P processes increases quite dramatically under the TechnoGarden scenario, but then

falls during the final decade. In these latter years anthropogenic N-fixation and phosphate mining decline as population growth (and hence crop production) starts to level-off, combined with improvements in farm management and thus efficiency of fertiliser application. Nevertheless, Ecological Overshoot remains well above one at the end of the study period for all the N and P processes considered, with a number of the processes exhibiting higher overshoot values at the end of the period than at the base year.

In the case of S it is interesting to note that the two processes for which Ecological Overshoot is less than one, i.e. net primary production and river export, the level of overshoot continues to drop. This example illustrates how not only overshoot but also 'understood' (i.e. regenerative capacity > ecoconsumption) can be problematic. Undershoot means that natural processes (especially soil erosion and river export) move S away from the terrestrial biosphere at a faster rate than human processes can add S to terrestrial biosphere. Under the TechnoGarden scenario, where S emissions from coal and other forms of anthropogenic combustion quickly start to fall away, the situation becomes more pronounced.

9.6 Key Points of Discussion

Soil S Deficiency

Although S deficiency within soils is not nearly as well researched and understood as for many other nutrients, there appears to be growing interest in the topic over the last few years (Jez, 2008; Ingenbleek and Kumura, 2013). Ingenbleek and Kimura (2013, pp.425–426) note that "a large number of field studies have provided continuing gains in fundamental and applied knowledge and have led to the overall consensus that SO_4^{2-} deficiency is a woldwide problem in the plant kingdom…SO_4^{2-} deficiencies have detrimental effects on most crops in Africa and Latin America but reach the highest incidence in southeastern Asia…Intensive agricultural production, lack of animal manure, and the use of fertilizers providing N, K and P substrates but devoid of SO_4^{2-} salts may further aggravate the imbalance within soils". Our understanding of the implications for human health of S deficiency is still in its infancy. Nevertheless, S deficiency has already been linked to a variety of health problems including autism, preecalmpsia, anaemia, cardiovascular disorders, and stroke (Hartzell and Seneff, 2012; Seneff *et al*. 2012; Ingenbleek and Kimura, 2013).

The growing undershoot of terrestrial S processes under the TechnoGarden scenario highlights the importance of system thinking, including analysis of interrelationships and trade-offs, in

relation managing human impacts on the global biogeochemical cycles. Under the TechnoGarden scenario there is a very strong emphasis on reducing global C emissions to help reduce impacts on climate. This includes both greater use of agricultural crops for energy, and reductions of fossil fuel combustion. Acknowledging that high atmospheric S is itself associated with adverse effects (soil acidification, health impacts), one of the interesting and unintended implications of reducing C emissions under the TechnoGarden scenario is that the rate of S depletion within the terrestrial biosphere, including soils, increases. Moreover, increasing reliance of biomass products as a fuel source adds further to the 'mining' of soil nutrients by agricultural activities. These types of dynamics are important not only for the S cycle, but also for the N and P cycles.

The Importance of Redundancy in Maintaining Resilient Economic Systems

Significant work has been undertaken over the last two decades in helping to understand and explain the conditions that contribute towards resilience within ecological systems. In particular, it is suggested that multiple species within the same functional group provides 'insurance' against environmental fluctuations, by increasing the chance that at least some species will respond differently to variable conditions, and that the functions performed by species under stress can be maintained by other species (McCann, 2000). Interestingly, the experience of building and experimenting with Ecocycle has brought home the importance of such ideas also to the understanding of economic systems. Note in these regards that it is possible under the TechnoGarden scenario for society continously to reduce consumption of energy commodities, while still increasing GDP per capita. In part this is because there is a range of different types of energy commodities incorporated within the model; small movements in supply and demand among these different commodities help to 'iron-out' price fluctuations and maintain economic stability. By contrast, when trial-runs were undertaken with Ecotime that incorporated non-negligible restraints on growth in the supply of timber reserves, the modelled economic system very quickly experienced enormous growth in commodity prices, and then collapse of all economic activities.

Two key conclusions are evident. On the one hand, we can conclude that Ecocycle is only a model, and likely requires further refinement to depict demand and supply behaviours meaningfully in relation to timber commodities. Timber products differ by type and location of supply possibilities for substitution with other types of commodities exist – for example, there has been a huge proliferation of bamboo products in recent years and metal products can clearly perform many of the functions of timber in construction. Such dynamics are not

presently incorporated within the model. On the other hand, the behaviour depicted by the current version of Ecocyle emphasises that in a world subject to resource constraints and potentially fluctuating environmental conditions, there is real value in maintaining diversity within the economic system, i.e. ensuring that different types of activities are able to produce commodities that perform similar functions.

The need for Improved Understanding of the World's Agri-fibre Systems

Related to the preceding paragraphs, there is a greater need for information and understanding of the global fibre production system, including its possible future trajectories. It appears to be widely anticipated that demand for timber and agricultural land shall continue to place pressure on forest reserves, at least for some time. For example, even under the TechnoGarden scenario, the rate of loss of undisturbed forests is only slightly below the historic rate, and at the historic rate for the Global Orchestration scenario (Alcamo *et al*., 2005a). It is not unforeseeable that the proportion of fibre provided by agricultural plantations will increase significantly in future years, especially if actions are taken to reduce removal of presently undisturbed forests. Like all agricultural activities, fibre plantations utilise a scarce land resource, and in these regards must act in competition with other agricultural activities. Moreover, if producers seek to increase outputs per hectare from plantations then we should also expect some application of nutrients to enhance land productivity, which has important biogeochemical implications. It is somewhat surprising that while a significant amount of research has been undertaken over the last few years in examining such issues in regards to energy crop production, there is relatively little information available or outlook studies undertaken in regards to agri-fibre systems.[218]

9.7 Model Caveats

Throughout the course of developing the Ecocycle Model, a number of important aspects have either not been addressed or require further work. Specifically, these include the nature of the global environment-economy system, the importance of causal structure in determining dynamics, building confidence and uncertainty analysis. These are discussed further below.

[218] Note, for example, that the outlook study for global fibre supply available on the FAO website (http://www.fao.org/forestry/outlook/2382/en/, Accessed 31 March 2014) was undertaken in 1995, with an outlook to the year 2010.

The nature of the global environment-economy system

Ecocycle represents an attempt to model human perturbation of the global environment-economy system. This system is a complex system. It is characterised by many stocks, interconnected feedback loops and non-linearities. As noted originally by Forrester (1969), the feedback loops within complex systems may be reinforcing (i.e. positive) or balancing (i.e. negative). Reinforcing loops are characteristic of all growth processes and tend to be goal divergent, often departing exponentially from some unstable equilibrium, while balancing loops typically goal-seek regulating behaviour toward some equilibrium (Forrester, 1969). Balancing loops regulate behaviour by depressing the regenerative characteristics of reinforcing loops – often resulting in equilibrium of steady state. Moreover, these feedbacks loops typically result in non-linear transition pathways that are extremely difficult, if not impossible, for the unaided human mind to intuitively guess or predict. Complex systems are often counterintuitive, remarkably insensitive to change in most system parameters, contain influential pressure points often in unexpected places, and policies thought to improve the system in the short run may make it worse than intended in the long run. Importantly, the "acceptance of the non-linear nature of systems shifts our attention away from the futile effort to measure accurately the parameters of systems [instead focusing our] attention on the far more important matter of system structure" (Forrester, 1969, p.108).

The importance of system causal structure

The purpose of the Ecocycle model is to gain insight into how humans are disturbing the global biogeochemical cycles. Approximately 70 stocks, 250 flows, and 600 converters make up the causal structure of Ecocycle.[219] Underpinning this causal structure is the conceptual framework developed in Chapter 3 and operationalised in the Chapter 7 DGES and Chapter 8 DGBCM models. These models are based, in turn, on the environmental and economic datasets developed in Chapters 4 and 5. While every attempt has been made to use the best available information, this information is, however, still far from perfect – many of the stated values are derived through balancing equations and have high levels of certainty. Moreover, Ecocycle is only a partial representation of the global environment-economy system. In particular, Ecocycle contains many exogenous inputs that, depending on the model boundary, represent complex systems in their own right, e.g. climate, society, culture, politics, and so on.

[219] Despite having only used 70 stocks to assess human perturbation of the biogeochemical cycles, it should be noted that 10 of these stocks have more than 500 associated feedback loops, and 1 stock is involved directly in over 12,500 feedback loops.

Nevertheless, it is the belief of the author that the Ecocycle model is useful even at this preliminary stage of development.

First, it provides a systems approach to considering how humans impact on the biogeochemical cycles. Specifically, this is achieved through the 30-year simulation of the integrated DGES and DGBCM models under two clearly stated global development scenarios. This integration is crucial to understanding environment-economy trade-offs which may exist in the future. Second, as demonstrated earlier in this chapter, change in exogenous inputs may be accounted for in the careful scenario development. Third, even in the absence of perfect data inputs, the information utilised is able to generate likely behaviour modes. It may be argued that these modes, which are based on Ecocycle's underlying structural dynamics, are more important than the exact data values used within the model. Even large changes in the exogenous inputs, for example, do not change the resulting behaviour of key reporting outputs. Importantly, Ecocycle is not intended to predict the future, but to gain insight into plausible 'transition pathways' under different development scenarios. Or, put alternatively, it is the underlying causal structure, rather than precise numerical inputs, that is important.[220]

Building model confidence

The validation or verification of Ecocycle can only be judged against its intended purpose. Unfortunately, like all computer models of complex systems, there is no mathematical or absolute proof that Ecocycle may fulfil its purpose. Furthermore, we can conclude that Ecocycle is inherently imperfect. Like all models, Ecocycle represents a simplification of reality. It is not so much whether Ecocycle is valid or not, but whether it is useful. In this regard, several confidence building tests exist, including:

- *Comparison with historical patterns*. The model may be back cast and checked against known real world information. Nevertheless, it is important to note that although a model may produce results that compare favourably with historical patterns this does not necessarily mean that a model will perform well when looking in the future. Historical trends may omit thresholds, stochastic events or emergent properties that could change an existing trend or pattern.

[220] Arguably, it is more serious to omit a causal relationship than to include it at low accuracy within a plausible range of uncertainty. Omission of a key relationship for whatever reason is equivalent to saying that this relationship makes no difference to the outputs produced by the model – this is clearly incorrect.

- *Verification*. This includes running the model in an independent manner (usually by a other researchers) to learn if the results match published results (Ford, 2010). The findings of Ecocycle may also be verified against independent models, with similar intents, developed by other researchers. Such verification has been undertaken, to some extent, through the process of implementing and reviewing the MA scenarios. The MA employed various models (including population, economic, land use change, food demand and agriculture) to quantify different aspects of the scenarios. A series of iterative adjustments were made to Ecocycle, up to the point where both inputs and outputs of the model became generally consistent with the two MA scenarios considered.
- *Extreme behaviour*. This test involves asking whether the model makes sense even when its input takes on extreme values. This may involve setting exogenous inputs to zero, and/or large numbers, to see if the model behaves appropriately. It may also involve ensuring that physical stocks do not become negative.

Moreover, leading practitioners of System Dynamics have described a plethora of useful tests which may be undertaken to build confidence in a model – see, for example, Forrester (1969), Forrester and Senge (1980), Richard and Pugh (1981), Kitching (1983), Rykiel (1996), Ruth and Hannon (1997), Sterman (2000), Meadows and Robinson (2007), Ford (2010), and Ruth and Hannon (2012).

Dealing with uncertainty

It has not been possible in the limited scope of this thesis to deal with uncertainty. It is, however, recognised that sensitivity and uncertainty analysis is critical for building confidence in the results and findings drawn from Ecocycle. Sensitivity analysis is essential for learning how the general patterns of behaviour exhibited by Ecocycle change in response to input parameters – narrowing down key drivers of change for each scenario simulation. Sensitivity analysis typically involves selection of an exogenous input variable, changing its value and running the simulation. If similar numerical, behaviour modes, or policy outcomes occur between simulations then the model is said to produce 'robust' results (Sterman, 2000; Ford, 2010).

It is important to note that although an exogenous input variable may be highly uncertain, this uncertainty should not be given as a reason for omitting this variable from the model. While sensitivity analysis may be used to identify the key exogenous drivers of change, uncertainty analysis adds value by investigating these parameters further. Two types of uncertainty

commonly exist in System Dynamics modelling, namely structural and parametric uncertainty. On the one hand, structural uncertainty comes down to whether or not omitted system structure will have a stabilising or de-stabilising impact on model results (Ford, 2010). This is arguably more difficult to establish. On the other hand, parametric uncertainty may be numerically determined using appropriate sampling methods. Ford (2010) notes that it is an unfortunate misconception that comprehensive uncertainty analysis of Systems Dynamics model is impossible. He notes that this misconception is the result of lack of knowledge of sampling methods. Sampling methods enable us to deal with uncertainty by running numerous experiments with a model. Common sampling methods such as random, stratified, importance sampling have all been applied in System Dynamics modelling. Moreover, it has been shown that Latin Hypercube Sampling is particularly effective in dealing with uncertainty in System Dynamics models (McKay *et al*., 1979; Reilly *et al*. 1987; Ford, 2010). While establishing sampling intervals is a cumbersome, but relevant process, it has simply been beyond the time available for this thesis to undertake.

Chapter 10

Conclusion

10.1 Introduction

This thesis began, in Chapter 1, by stipulating the broad aim for the research as progressing sustainability through the development and application of an integrated systems modelling framework of the coupled economic and global biogeochemical cycling systems. This is clearly a worthwhile goal, given the essential role of global biogeochemical cycles in maintaining and regulating the conditions necessary for life on Earth, as well as supporting the provision of the full range of other services provided by the biosphere to humanity. Increasing awareness of biogeochemical-related problems, including global climate change, soil acidification, and freshwater eutrophication is now placing an increasing need to consider the global biogeochemical cycles in a sustainability context. Current research on non-equilibrium ecology, and other systems-based topics, also strongly supports this conclusion. Coupled environment-economy systems are complex and adaptive systems that, when subject to significant perturbation, have the potential to transition to new stability domains that are not only less desirable, but potentially catastrophic to human existence.

Admittedly, the research aim was ambitious for one person to seek to achieve within the course of only a doctoral research programme. Nevertheless, a number of important contributions have been made within this thesis, making some meaningful progress towards the achievement of that broad aim. In support of this conclusion, this final chapter of the thesis returns to the set of objectives proposed in Chapter 1 to support the research aim, and reflects on the extent to which those objectives have been met by the work presented. Key theoretical, methodological, and empirical contributions made by the thesis are also summarised, along with principal limitations and areas for future research. It is worth noting that in addition to submission of this thesis and the acceptance of Chapter 6 and Appendix B for publication within internationally peer-reviewed journals, several additional co-authored journal articles, book chapters, and published research reports were completed during the course of this study. A full list of outputs, either directly or indirectly, related to this thesis follows this chapter.

10.2 Evaluation of the Thesis against the Research Objectives

Four research objectives were proposed within Chapter 1, each of which are discussed below.

10.2.1 Objective 1 – Theoretical Interpretations of Sustainability

The first objective was to:

> *Provide a theoretical interpretation of the concept of sustainability, uniquely focused on the topic of biogeochemical cycling. In turn, presenting a set of core sustainability principles that guide the development, use, and interpretation of the systems models and indicators developed in this thesis.*

In order to achieve this objective, Chapter 2 presents a literature review of sustainability in the context of the global biogeochemical cycles. This includes consideration of ethical (including emerging sustainability economics), ecological-economic, biophysical/thermodynamic, ecological and systems-based concepts. It is recognised that there are also a variety of other disciplinary viewpoints providing important contributions to our understanding of sustainability. These include, for example, institutional economics, feminism, political ecology, and development studies, to name only a few. A narrowing of the ambit and definition of the sustainability concept and, in turn, the scope of this thesis has been necessary to ensure tractability. Specifically, the thesis has focused on sustainability in the context of the biogeochemical cycles and systems modelling approaches.

The key principles for sustainability identified in Chapter 2 relate to the decoupling of material and energy throughput from economic production, the efficient use of natural capital, and maintaining the economy within an appropriate scale relative to the biosphere. Also important are the systems-related concepts of maintaining viability loops and resilience. These principles direct the content of the research by drawing attention to the importance of first establishing a static model (Chapter 3), populated with baseline information, from which we can understand the current structure and state of biogeochemical processes (Chapters 4 and 5), and monitor future progress in regards to decoupling, efficiency, and scale concerns. Providing indicators is also important, as these are a means of simplifying a system to help understand, communicate and monitor change (Chapter 6). The utility of dynamic models

(Chapters 7, 8 and 9) in achieving the aim of the thesis also becomes apparent when we recognise such models as 'learning tools' that help select resilient-building strategies, by providing capacity to envisage futures and actions that might attain, or avoid, outcomes.

10.2.2 Objective 2 – Static System Analysis

The second objective stipulated for the thesis was to:

> *Undertake a descriptive and functional analysis of the Earth's biogeochemical cycles, focusing on the so-called 'grand nutrient cycles' of C, N, P and S. This analysis will enable us to understand the current state of these cycles, including answering questions such as: 'What do current material flows and their transformations look like?', 'How do human activities influence these cycles?' and 'Which human activities are responsible for the greatest impacts?'*

In order to realise this objective, the thesis begins with the formulation of a static framework (Chapter 3), referred to as the 'ESAM', enabling us to comprehend and describe the global biogeochemical cycles, and how these interact with the global economic system. The ESAM is conceptually consistent with a view of the human economy as existing, at least in a physical sense, within a wider ecological system. It is also systematic, with careful attention to the inclusion of all mass flows for a particular biogeochemical cycle. Nevertheless, the ESAM framework is pragmatic, measuring flows internal to the economy only in financial terms, and material flows within the environment and between the environment and economy in mass terms.

One potential extension to the ESAM framework and its empirical accounts is to utilise a physical numeraire for the within-economy flows. Essentially, this would result in the development of a full PIOT for each element considered, which would enable the development of additional indicators. It is also noted that with such information it would be easier to investigate how changes in resource inputs to an economic system are connected to changes in residual outputs from that same system. This does not imply, however, that physical numaraire are necessarily better, or should be used in replacement of financial numaraire. In these regards it is particularly noted that the provision of service activities within an economy often do not involve an identifiable exchange of mass, yet the financial exchanges associated with those activities are very important, indirectly, in determining the nature and rate of

physical processes elsewhere within the system. Ideally, an accounting framework for an economic system would include both physical and financial numaraire.

In order to populate the ESAM framework, several substantial IO accounts were developed. First, Chapter 4 describes the development of a comprehensive set of material flow accounts for the biogeochemical cycles of C, N, P, and S. These are essentially the mass flows crossing the environment-economy interface, and resulting from the human use of raw materials (e.g. biomass extraction, biomass production, minerals extraction, fossil fuel extraction, industrial N fixation) and production of residuals (e.g. atmospheric emissions, residuals disposed to land). Also included are mass flows associated with wastes production (e.g. livestock excrement and crop residuals, municipal solid waste, ISW, coal ash P, municipal wastewater, industrial wastewater) and treatment (e.g. landfill deposition, combustion, paper recycling). This information is all summarised in diagrammatic form by a Sankey diagram for each element (Figures 4.1–4.4). Among the information apparent from these diagrams is the significant role of the global economy in 'metabolising' high-energy commodities produced by natural biogeochemical processes. Biomass and fossil fuels, in particular, are demanded in huge quantities by the global economy and that matter, once passed down economic supply chains, is re-released to the environment largely as dispersed and low-energy residuals. It is an unfortunate paradox that there exists substantial demand for N and P compounds for agriculture, while at the same time there are significant production of those same compounds in unused wastes. This highlights a clear need for technologies and practices that greatly improve waste recycling and the efficiency of natural resource utilisation.

Next, Chapter 5 completes the IO or 'extended material flow' accounts for biogeochemical cycles by compiling the within-environment flows and net changes in environmental stocks accounts. Compilation of these accounts required development of a large set of mass balance equations for biogeochemical process occurring with the atmosphere (e.g. natural N fixation, CH_4 oxidation), terrestrial biosphere (e.g. litter and soil processing), oceans (e.g. ocean NPP, ocean carbonate cycling), and lithosphere (e.g. fossil fuel formation). Additionally, it required quantifications of exchanges between the atmosphere and terrestrial biosphere (e.g. aeolian emissions, wildfires), terrestrial biosphere and oceans (e.g. river export), oceans and atmosphere (e.g. CO_2 exchange, wet and dry deposition), oceans and lithosphere (e.g. organic and inorganic sediment burial), lithosphere and terrestrial biosphere (e.g. weathering, P lithification), and lastly, lithosphere and atmosphere (e.g. volcanic emissions).

Despite the relative conceptual simplicity of the mass flow accounts, it must be stated that the work required for Chapters 4 and 5 was the most laborious and painstakingly difficult component of the research. More than 300 different literature sources were reviewed, on topics as broadly ranging as the nature of Redfield ratios in marine plants, sulphide removal from petroleum refinery wastewater, leaf nutrients absorbed during plant senescence, and landfill methane emissions. In addition to the numerous book and journal publications reviewed, reference was also made to a number of statistical databases and data compilation methodologies. The accounts presented in this thesis represent a unique compilation of scientific and financial information pertaining to the current state of the global C, N, P, and S cycles. Of particular relevance to the international research community will be the comprehensive coverage of both natural and anthropogenic processes, and the wide level of industrial detail provided for anthropogenic flows.

Given the time involved, only the grand nutrient cycles of C, N, P, and S were considered under Objective 2. It is, however, important to recognise that other cycles are also of great importance and worthy of similar research. Particularly worthy of future consideration are the cycles related to hydrogen and oxygen. Water (comprised of hydrogen and oxygen) is an essential compound for life, a key transporter of materials and is a common reactant and product of many biogeochemical processes. Similarly, oxygen is often a critical element in redox (oxidation and reduction) chemical reactions. Also worth noting is that there may be other limiting elements influencing the rate of flow of important environmental processes, e.g. the micronutrient iron required for ocean primary production (Martin and Fitzwater, 1988), and similarly, plants require magnesium in their chloroplasts to perform photosynthesis. Another potential avenue for future research is therefore the coupling of element cycles and the incorporation of such behaviours within dynamic models.

The inclusion of energy flows within the ESAM framework would, from an ecosystem and industrial ecology perspective, provide a more conceptually complete description of the biogeochemical cycles. While significant data and time constraints have prevented this from being possible within this thesis, it is identified as a highly worthwhile topic for future work.

10.2.3 Objective 3 – Indicator Development

The third core objective of the thesis was to:

> *Develop a suite of indicators that enable us to assess progress towards the goal of sustainability in relation to the Earth's biogeochemical cycles. Ideally, these indicators will have a wide scope, allow trends to be determined, and have pedagogic value.*

Any person engaged in producing a doctoral thesis will find themselves on a variety of occasions, whether it is at work, meeting friends or simply undertaking day-to-day errands, faced with the task of having to provide a summary of their research topic to a lay person. Such conversations have shown, unfortunately, that despite the immense importance of biogeochemical cycles to all humanity, very few people have even a basic understanding of these cycles and their relevance. As aptly noted by Meadows (1998), indicators not only arise from values, as we measure what we care about, they also create values, as we care about what we measure. If for no other than the pedagogical reason of creating an awareness of biogeochemical cycles and their importance to human well-being, indicators such as those presented in this thesis are important.

The ESAM and its various accounts (Chapters 3, 4 and 5) provide a wealth of information from which various types of indicators pertaining to the global biogeochemical cycles and associated human impacts may be calculated. Chapter 6 focuses specifically on developing a novel method, based on IO analysis, for deriving a suite of indicators that describe the level at which the global economy, through its transformation of useful resources (i.e. raw materials) into residuals (i.e. wastes, pollutants, emission), appropriates biogeochemical processes. In order to calculate these indicators, the thesis introduces a new concept of 'ecotime', defined as the average biogeochemical cycling time available for matter held within different environmental stocks (e.g. CO_2, plants, fossil fuels) to reach a selected biogeochemical process. The presented method makes it possible to compare the creation of ecotime by natural biogeochemical processes, with the consumption of ecotime by the global economy, thereby calculating the level of 'ecological overshoot'. The thesis also demonstrates the way in which ecotime appropriation can be traced through economic production chains, and ultimately attributed to final consumer goods. Additionally, Chapter 9 illustrates the use of ecotime

indicators within a dynamic model, as a means of monitoring change and assisting in the evaluation of alternative futures or scenarios.

On applying the ecotime methodology to the data compiled in Chapters 4 and 5, it is found that humans are placing significant pressure on the biogeochemical cycles. The global economic system is responsible for absorbing significant quantities of ecotime provided by the biogeochemical cycles, particularly in the C cycle, but also to a lesser extent in the N cycle. An investigation of the terrestrial and oceanic biogeochemical processes highlights that more than 20 years of the current rate of regeneration provided by the C cycle is appropriated by the global economy within just one year. In the case of the P and S cycles, and possibly also the N cycle, it would appear that 'undershoot' of biogeochemical processes is an additional problem that is likely to deepen over time. For the S cycle in particular, natural processes (particularly soil erosion and river export) are responsible for moving elements away from the terrestrial biosphere at a greater rate than the addition of those elements back to terrestrial systems via human processes. The current high rate of natural removal of S from terrestrial systems reflects, in part, landscape changes that exacerbate erosion, and the large quantities of biomass S resources that are transformed by the economy into dispersed wastes effectively 'flushed away' by freshwater systems. Interestingly, the level of undershoot of terrestrial S processes is only likely to increase from measures designed to reduce perturbation of the global C cycle. This highlights the importance of systems thinking, including analysis of interrelationships and trade-offs, in relation to managing human impacts on the global biogeochemical cycles.

Like other concepts such as the Ecological Footprint, Emergy Analysis, and Cumulative Exergy Consumption, Ecotime Analysis has the potential to create awareness and fruitful debate regarding the appropriate scale of economic activities relative to the environment that sustains all humanity. Ecotime Analysis as presented in this thesis, however, has sought to avoid several of the methodological difficulties inherent in these alternative indicators. Most importantly, it is recognised that the environment-economy system is *cyclical* – even matter that is an output of a particular ecological process will eventually become an input to that same process. By applying time as the numaraire, it becomes possible to present meaningful comparisons of ecological commodities relative to important biogeochemical cycles, while still accounting for the numerous production relationships that connect those commodities within the environment-economy system in a cyclical fashion.

Nevertheless, the ecotime indicators are not without limitations. Perhaps of most importance is the need to compile a detailed database of biogeochemical flows for calculation of the indicators. As is demonstrated by the laborious work conducted within Chapters 4 and 5, such information is dispersed, often incomplete, and difficult to reconcile. On a related topic, it is acknowledged that disaggregation of the lithosphere stocks/processes into sub-stocks/sub-processes is likely to improve the ecotimes estimated within Chapter 6.[221]

10.2.4 Objective 4 – Dynamic System Analysis

The final objective was to:

> *Construct an integrated dynamic global simulation model of the Earth's biogeochemical cycles, incorporating both the environment and economy and their interdependencies. This dynamic model will provide a synthesis of the information obtained and analysis undertaken of the biogeochemical cycles, in a way that can be easily communicated to the wider community. This will include functionality for testing what might happen under alternative future global development scenarios.*

To address this objective, Chapter 7 describes the development of a dynamic simulation model for the global economy, Chapter 8 presents a dynamic simulation model for the global environment, and a prototype integrated dynamic simulation model, termed 'Ecocycle' is described in Chapter 9.

As noted in Chapter 7, the CGE models that presently constitute the mainstay for policy-oriented research are subject to some important limitations in regards to the treatment of time and the ability to simulate economic pathways or trajectories. Motivated by a desire to address some of these concerns, Chapter 7 demonstrates the way in which the behavioural relationships underpinning a standard CGE model may be formulated as a System Dynamics model. This new 'Dynamic General Equilibrium-*Seeking* Model', relies on price-related

[221] The calculation of ecotimes requires estimates of the residence times for elements passing through the lithosphere stocks. It is, however, likely that differences exist in residence times for crustal versus mantle lithosphere stocks. While average residence times are used, it is acknowledged that our understanding of mantle processes is still very limited. Separating the lithosphere into crustal versus mantle sub-stocks/sub-processes would at least improve the estimates of residence times for lithosphere stocks. Similarly, disaggregating mined S and P, from other S and P stocks in the crust could also potentially improve the ecotime estimates.

balancing feedback loops to simulate the self-regulating behaviour of dynamic economic systems, rather than on an optimisation procedure as in the standard CGE approach. Not only does the model simulate time-path trajectories for economies transitioning towards equilibria, it does this without many of the computational problems inherent to standard CGE analysis. Additionally, the Systems Dynamics framework provides for better integration of other simulation models, including ecological stock and flow models, thereby facilitating modelling of coupled environment-economy systems.

Even putting aside these advantages, it is considered that the System Dynamics approach to economic modelling has significant value, simply for its ability to foster understanding of economic systems, as well as making transparent the underlying assumptions inherent in many economic models. Standard CGE models are typically implemented within specialist programming languages, that require steep learning curves. This black box approach to modelling limits the utility of models as a learning tool, masking important assumptions and discouraging constructive critique. By comparison, System Dynamics modelling software is relatively intuitive and easy to implement. The time-path trajectories produced by the models help users envisage the interplay of causal feedback structures underpinning model outcomes. Not only does this help transfer understanding of the structure and behaviour of economic systems to users, it also provokes critical review of the sufficiency of models in representing those systems.

In addressing Objective 4, the development of Ecocycle represents one of only a very few integrated models of the Earth system, and perhaps the only simulation model that explicitly captures the dynamic relationships that exist between the biogeochemical cycles and human activity. It is, however, acknowledged that significant opportunity exists to improve or extend the modelling of coupled economic and biogeochemical cycling systems – several of these are listed in Table 10.1. Further work on model validation, verification, and uncertainty analysis is also clearly required. These limitations help define the next steps, or opportunities, for further development of the work conducted during the course of this thesis.

The extent of the topics identified for further development, which have been a necessary comprise to ensure tractability and completion of this thesis, should not detract from the contributions made in constructing and applying the Ecocycle simulation model. Even with application of the two scenarios thus far considered, some interesting points of reflection have arisen. Without *very* significant changes from the current global growth path trajectory,

human perturbation of the biogeochemical cycles is likely to continue to increase significantly over the next few decades. The cycles are highly interconnected and, unfortunately, actions taken to reduce impacts on one cycle may not operate in the same direction on another cycle. Additionally, Chapter 9 pays specific attention to the need for further information on the likely management practices and biogeochemical cycling implications associated with future intensification of agri-fibre systems, and highlights the possible importance of redundancy and diversity in maintaining resilience within economic systems.

Table 10.1 Current Limitations of the Dynamic Models/ Topics for Further Research

Topic	Relevant Chapters	Explanation
Commodity demand functions	Chapters 7, 9	The commodity demand functions for households, government and investors could be improved. One possibility is the use of a Constant Difference of Elasticities function whereby an agent's mandatory (e.g. substistence food) versus discretionary (e.g. entertainment) expenditure are determined by income effects as well as the relevant prices of commodities. Other possible functional forms also deserve investigation.
Industry technical coefficients	Chapters 7, 9	Although the dynamic economic model captures substitutions between intermediate inputs, labour and capital, it does not take account of substitution or technical change in the intermediate inputs. While this is common among CGE models, it becomes particularly questionable when considering dynamic applications that run over longer periods (i.e. > 20 years). An inability to account for technical change or substitutability in intermediate inputs potentially leads to model instability.
Donor versus receptor determined flows	Chapters 8, 9	The strength of the GBCM lies in the integration of the element cycles. One key weakness, however, is that only donor stocks are used to calculate process rates. For some processes (e.g. C uptake by the oceans, $CaCO_3$ dissolution), rates may be better driven from a receptor stock, or a combination of donor and receptor stocks approach.
Climate feedbacks	Chapters 8, 9	Climate factors (e.g. temperature, pressure, humidity) are an important influence on the rates at which different biogeochemical processes occur. Moreover, climate plays a role in the movement/ transport of material through the biosphere. The nature and rate of biogeochemical processes, in turn, are key influences on climate. To some extent the omission of climate feedbacks is justified by the relatively short-term focus of the scenarios. Nevertheless, if humanity's impact on the environment is to be better understood a longer view is required. A challenge is to take general patterns of behaviour observed from detailed climate models, and use this information to update and revise more general and simple scoping models.

10.3 Creation of Symmetric Input-Output Tables

A review of the contributions of this thesis would be incomplete without specific mention of Appendix B. Modelling is essentially about making sense of the world by representing real-world systems in a less complex form. Appendix B 'Estimation of Symmetric input-Output Tables' provides a set of tools that assist us in representing and summarising system flows, in a manner that is useful for particular types of economic models. Specifically, a methodology based on non-linear optimisation is presented that enables the development of balanced Symmetric IO Tables (either commodity-by-commodity or industry-by-industry) through any combination, including hybrids, of technology assumptions, while ensuring that no negative coefficients are produced. This methodology will be of particular interest to practitioners engaged in development of National Accounts, analysts undertaking economic or environmental impact assessment based on IO analysis, and CGE modellers. The methodology has been employed in this thesis to construct accounts employed in calculation of some of the ecotime indicators (Chapter 6), and compilation of the base-year accounts necessary for operation of the DGES (Chapter 7) and Ecocycle (Chapter 9) models.

List of PhD Outputs

During the course of this research four papers were accepted for publication in internationally peer reviewed journals including three papers as lead author, while one further manuscript has been submitted to a journal and is awaiting confirmation of acceptance. Two book chapters were also published. Finally, several published reports have been written under contract for commercial clients. To greater or lesser degrees, all of the research outputs presented below are based on datasets, methodologies or simply insights gained during the course of preparing this thesis.

Journal papers

Peer-reviewed published or accepted for publication journal papers

Patterson, M. G., McDonald, G. W., & **Smith, N. J.** (2011). Ecosystem Service Appropriate in the Auckland Region Economy: An Input-Output Analysis. *Regional Studies, 45*(3), 333-350.

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Smith, N. J., McDonald, G.W. and Murray, C. F. (2014). The Costs and Benefits of Water Demand Management: Evidence from New Zealand. *Water and Environment Journal* (forthcoming).

Smith, N. J., McDonald, G. W. and Patterson M. G. (2014). Is there overshoot of planetary limits? New indicators of human appropriation of the global biogeochemical cycles relative to their regenerative capacity based on 'ecotime' analysis. *Ecological Economics, 104*, 80-92.

Journal papers submitted to peer-reviewed journals for publication, but awaiting confirmation of their acceptance

McDonald, G. W., Cardwell, R. J., **Smith, N. J**., Kim, J., van Delden, H., & Murray, C. F. (2014). Clustering Geographic Information System (GIS) Polygons: A practical approach to urban land use mapping for spatially-explicit dynamic modelling. *Land Use Policy* (submitted).

Published book chapters

McDonald, G. W., **Smith, N. J.** & Murray, C. F. (2014). Economic impact of seismic events: Modelling. In Seville, E. & Vargo, J. (Eds) *Encyclopaedia of Earthquake Engineering* (forthcoming).

Patterson, M. G., McDonald, G. W., Probert, K., & **Smith, N. J.** (2008). Biodiversity of the Oceans. In M. Patterson & B. Glavovic (Eds.), *Ecological Economics of the Oceans and Coasts* (p.51-72). Cheltenham, UK: Edward-Elgar Publishing.

Selected Reports

Published peer reviewed reports

Auckland Regional Council. (2010). State of the Auckland Region 2009. Auckland: Auckland Regional Council. ISBN 978-1-877540-45-5 (Member of Project Team)

Lennox, J., Andrew, R., Drysdale, D., Lenzen, M., McDonald, G., Ndebele, T., Peters, G., **Smith, N**., Wiedmann, T. & Zhang, Y. (2010). Greenhouse Gases Embodied in NZ's Trade: Final Report. A report prepared for Ministry of Agriculture and Forestry. Wellington: Ministry of Agriculture and Forestry.

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Appendix A

Input-Output Analysis

A.1 Brief History of Input-Output Analysis

Wassily Leontief (1906-1999) is credited with the development of IO analysis.[222] IO study's the interdependence of the producing and consuming sectors in an economy. An IO table is an empirical formulation of these relationships. In 1936, Leontief published an IO table for the US economy which was followed five years later by his famous book *The Structure of American Economy* (Leontief, 1941). Leontief won the 1973 Nobel Prize in Economics for his development of IO analysis.

As a precursor to Leontief's contribution, Francois Quesnay developed the *Tableau Economique* in 1758.[223,224] Like Leontief's IO table, Quesnay's *Tableau* highlighted the interdependence between the production sectors of the economy; by tracing successive rounds of wealth generated initially by agricultural expenditure. The development of IO was further laid in the 1870s, most notably by the contribution of French-Swiss economist Léon Walras who in 1874 published his *Elements of Pure Economics* (Richardson, 1972; O'Connor and Henry, 1975). It has been argued by Richardson (1972) that Leontief simplified Walras' General Equilibrium approach by aggregating commodities to form industries and abandoned both the supply equations for labour, and the demand equations for final consumption.

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[222] Similar ideas were also conceived at around the same time by Peiro Sraffa (1960) and the French mathematician, Father Maurice Potron (Abraham-Frois and Lendjel, 2006).

[223] A number of economists preceding Quesnay also provided precursory ideas. Kurz and Salvadori (2000) explain how William Petty (1690, 1691) described the characteristics of production, distribution, and disposal of the wealth of a nation as closely interconnected. Petty further recommended that "just accounts might be kept of the People, with the respective increases and decreases of them, their wealth and foreign trade" (Stone, 1973, p.143).

[224] Leontief was born and educated in Russia. It is worth noting that in 1923 a Russian statistician, V. G. Groman, also took up the idea of applying Quesnay's Tableau Economique to a real economy. During that year, Groman presented both a paper on the topic to the Chief Board of Gosplan, and a draft of a balance of the national economy (Jasny, 1962). Shortly following, the Central Statistical Office prepared a first balance of national income for 1923/24.

A.2 Description of Input-Output Analysis

A.2.1 The Input-Output Table

At the most basic level, an IO table fulfils two functions. First, it is a descriptive framework showing the relationships between inputs and outputs of sectors within in an economy. Second, given certain assumptions it is an analytical tool that may be used to measure the impacts of changes within an economy.

A conventional IO analysis typically begins with the construction of a 'transactions table' (Figure A.1). This table records, in value terms, the various economic flows within the economy for a given period. The columns show industry purchases from other industries and primary inputs, while the rows show sales to other industries and final demand. The table is divided into four quadrants. Quadrant I, top left, shows the flow of goods that are both produced, and consumed, in the process of production. Quadrant II shows the final demands (e.g. households, government and exports) for the output of each producing industry, while Quadrant III shows the primary inputs (e.g. wages and salaries, profits, imports and taxes) paid out by the productive industries. Quadrant IV records the primary inputs that go directly into final demand.

IO analysis introduced the assumption of a technological relationship between industries whereby the purchases of any industry (except final demand) from other industries depend, via a linear production function, on the level of output of the purchasing industry (Richardson, 1972). Based on this assumption one can construct a table of 'technical coefficients'. Technical coefficients are calculated by dividing every item in Quadrants I and III by the total of the column in which the item is recorded (O'Connor and Henry, 1975). With respect to Figure A.1 for example, the internal flow within Agriculture, 2.180, when divided by 200.345 (the row column), gives a technical coefficient of 0.0109. This may be interpreted as meaning for every $1 of agricultural output, $0.0109 of inputs is required from within the agriculture industry itself. Technical coefficients show the direct or first order effects of changes in final demand. To study second and higher order effects interdependence coefficients must be calculated (O'Connor and Henry, 1975).

		Intermediate Demand				Final Demand					
		Agriculture	Industry	Services	Total Inter-Industry	Household Consumption	Government Consumption	Capital Formation	Exports	Total Final Demand	Total Output
		I				II					
	Agriculture	2.18	81.69	1.14	85.01	62.11	0.80	2.67	49.75	115.34	200.35
	Industry	27.71	98.04	25.46	151.20	207.09	14.82	61.73	103.28	386.92	538.12
	Services	11.02	32.24	19.49	67.75	139.20	50.85	6.43	42.09	238.56	301.31
	Total Inter-Industry	40.91	211.97	46.09	298.96	408.39	66.47	70.83	195.12	740.81	1,039.78
		III				IV					
Primary Inputs	Imports	15.29	119.84	7.86	142.99	62.30	1.76	25.98	3.35	93.39	236.38
	Indirect Taxes	11.56	49.26	9.20	70.02	31.84		0.89	3.18	35.95	105.96
	Subsidies	-7.32	-5.85	-6.70	-19.87						-19.87
	Wages, Salaries, Profits	133.60	150.40	229.57	513.57				33.91	33.91	547.49
	Depreciation	6.30	12.50	15.30	34.10		2.50	-1.10		1.40	35.50
	Total Primary Inputs	159.44	326.15	255.22	740.81	94.18	4.26	25.77	40.43	164.64	905.46
	Total Inputs	200.35	538.12	301.31	1,039.78	502.57	70.74	96.60	235.55	905.46	1,945.23

Figure A.1 Input-Output Table for Ireland, 1960

Source: O'Connor and Henry (1975).

A.2.2 Input-Output Mathematics and Limitations

For a generalised economy, the transactions table may be represented in symbolic terms as per Figure A.2.

	Intermediate Demand			Total Final Demand	Total Output
	Industry 1	Industry 2	Industry 3		
Industry 1	z_{11}	z_{12}	z_{13}	y_1	x_1
Industry 2	z_{21}	z_{22}	z_{23}	y_2	x_2
Industry 3	z_{31}	z_{32}	z_{33}	y_3	x_3
All primary inputs	m_1	m_2	m_3		
Total Input	x_1	x_2	x_3		

Figure A.2 Input-Output Table in Symbolic Terms

To show how the independence coefficients are derived, we must first set out the various flows recorded in Figure A.2 as a system of linear equations:

$$x_1 = z_{11} + z_{12} + z_{13} + y_1$$
$$x_2 = z_{21} + z_{22} + z_{23} + y_2$$
$$x_1 = z_{31} + z_{32} + z_{33} + y_3 \quad .$$

Furthermore, we must calculate the technical coefficients, a_{ij}, can generally be calculated according to the equation $a_{ij} = \frac{z_{ij}}{x_j}$ where *i* represents the row, and *j* the column, in which a coefficient is located. By substitution, a set of simultaneous equations can be written as,

$$x_1 = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + y_1$$
$$x_2 = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + y_2$$
$$x_3 = a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + y_3 \quad ,$$

and in matrix form,

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}, \text{ or,}$$

$$\mathbf{Ax} + \mathbf{y} = \mathbf{x}. \qquad \text{(A.1)}$$

Mathematically, the vector of output $\mathbf{x}$ can then be estimated, through reorganisation, as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}. \qquad \text{(A.2)}$$

The identity matrix minus the matrix of technical coefficients, $(\mathbf{I} - \mathbf{A})$, is known as the 'Leontief matrix'. The inverse of the Leontief matrix, $(\mathbf{I} - \mathbf{A})^{-1}$, provides the matrix of 'interdependence coefficients' kniwn as the 'Leontief inverse matrix'. Once obtained, we can multiply the Leontief inverse matrix by any final demand vector in order to obtain the corresponding level of gross output required for each industry. The Leontief inverse matrix, thus, provides us with a very powerful analytical tool to measure the effects of exogenous changes in the economy (Richardson, 1972). It is worth noting that the Leontief inverse matrix may be used to undertake 'multiplier analysis' as is often undertaken in economic impact assessments.

Key IO assumptions include:

- *Time*. The IO approach generates relationships between the level of activity in an industry and the levels in its supplying industries. However, inputs (except with respect to service industries) must typically be produced and stored before they can be used. Importantly, a system of production may alter during the lag in time between production of a particular commodity and production of its relevant inputs. The IO approach, nevertheless, connects the current level of each industry with previous levels of its supply industries and subsequent levels of its supply industries by assuming constant technical coefficients over time. For this reason, the model is said to strictly apply only to only a stationary equilibrium system (Dorfman, 1954).
- *Aggregation*. Through aggregation, firms whose technical methods are not identical are grouped into a single industry. The IO approach assumes that the 'product mix' and input structure of the entire industry is constant and that all technically different segments of

the industry expand and contract in the same proportion (Dorfman, 1954; O'Connor and Henry, 1975). Careful attention must therefore be paid to the treatment of joint and secondary production.

- *Price effects*. Neo-classical economic theory states that the amount of each input, used in producing a given output, will respond to changes in relative input prices. The IO approach however ignores such substitutions.
- *Constant production functions*. The production function assumes that the quantity of each input consumed by an industry is directly proportional to the quantity of output produced by that industry. Constant proportionality is however only a crude approximation of actual productive relationships; many expenses do not increase in direct proportion to output (Dorfman, 1954). Economies and dis-economies of scale are examples.
- *Technological change*. IO coefficients provide a static snapshot of within economy flows; they do not consider change over time as occurs with technological progress.

A.3 Environmental Input-Output

IO has been extended to examine economy-environment interactions. Specifically, these are grouped into two approaches: (1) industry-by-industry approaches based on standard Leontief IO tables, and (2) commodity-by-industry approaches typically based on SUT where joint products are accounted for and the number of commodities usually exceeds the number of industries.

A.3.1 Industry by Industry Input-Output Approaches

The Cumberland Model, 1966

Cumberland (1966) is attributed with development of the first environmental IO table (Figure A.3). Cumberland added both rows and columns to the standard IO to identify the environmental benefits and costs associated with development. Of most interest are the last three rows, and the last column, of the table. The entries in row q are the estimated dollar valuations of environmental benefits of a project accruing to specific industries. Row c represents the environmental costs resulting from a specific project distributed by industry. Row a represents the net environmental benefits by industry, while column b records the post development costs by industry of restoring the environment to acceptable standards (Lonergan and Cocklin, 1985). Cumberland suggests the environmental factors to be considered would include as minimum water, air and open space. The key criticism that has

been levelled against the Cumberland's model is the difficulty of attaching pecuniary values to environmental impacts.

	Industry purchases	Final demand	Regional purchases	Exports	Total purchase from regional economy	Environmental balance
Industry sales						b
Value added						…
Total regional sales						…
Total imports						…
Environmental benefits	(+) q …	…				
Environmental costs	(-) c …	…				
Environmental balance	a = (q - c)	…				

Figure A.3 The Cumberland Model

Source: Cumberland (1966).

The Daly Model, 1968

The Daly model (Daly, 1968) is divided into four quadrants (Figure A.4). Quadrant 1 is similar to a standard IO table in that it shows the flows between economic industries. Analogously, Quadrant 4 records the flows between ecological spheres. Quadrants 2 and 3 record the flows between the economy and environment. Quadrant 3 accounts for the environmental resources utilised by economic industries (i.e. raw materials), while Quadrant 2 contains flows from economic industries to ecological spheres (i.e. residuals). Mixed financial and physical units are utilised in describing these flows.

Daly also proposed the calculation of technical coefficients by dividing each row element by its corresponding row total. This approach has been criticised on the basis that the economic and ecological flows are expressed in different units. Adversaries of Daly's model note that it is illogical when transferred to the ecological spheres as ecological commodities may have different numeraires, and thus cannot necessarily be aggregated.

	1 Agriculture	2 Industry	3 Households (final consumption)	4 Animal	5 Plant	6 Bacteria	7 Atmosphere	8 Hydrosphere	9 Lithosphere	10 Sink (final consumption)	Total
	Quadrant 1			*Quadrant 2*							
1 Agriculture		q_{12}					q_{17}				Q_1
2 Industry	q_{21}	q_{22}	q_{23}				q_{27}				Q_2
3 Households		q_{32}					q_{37}				Q_3
	Quadrant 3			*Quadrant 4*							
4 Animal											
5 Plant											
6 Bacteria											
7 Atmosphere	q_{71}	q_{72}	q_{73}	q_{74}	q_{75}	q_{76}	q_{77}	q_{78}	q_{79}	q_{710}	Q_7
8 Hydrosphere											
9 Lithosphere											
10 Sun											

Figure A.4 The Daly Model

Source: Lonergan and Cocklin (1985).

The Leontief Model, 1970

Leontief's (1970) environmental IO model is an adaptation of his standard IO model (Figure A.5). There are however two important points of departure. Firstly, there is an additional row recording the units of pollutants generated by industrial activity, and secondly, an additional column representing a pollution abatement industry.

	1 Agriculture	2 Manufacture	Pollution Abatement	Final Demand	Total
1 Agriculture	z_{11}	z_{12}	z_{13}	y_1	x_1
2 Manufacture	z_{21}	z_{22}	z_{23}	y_2	x_2
Pollutant	z_{31}	z_{32}	z_{33}	y_3	x_3
Value Added	m_1	m_2	m_3	y_4	

Figure A.5 The Leontief Model

Source: Adapted from Leontief (1970).

The pollutant row shows the amount of pollutant in physical terms, z_{31} and z_{32}, generated by each of the industries listed at the heads of the different columns. Cell z_{33} can be considered as the sum of the total amount of pollutant eliminated by the pollution abatement industry. The entry y_3 represents the total amount of pollution delivered to households, i.e. the tolerated amount of pollutants. Given that all pollutants are either eliminated or delivered to final demand, the total pollutants, x_3, is zero. In other words:

$$y_3 = z_{31} + z_{32} - z_{33}. \qquad \text{(A.3)}$$

Except for the entries recorded in the pollutant row, all entries are recorded in financial terms. Leontief (1970) derived these financial values from information concerning the total physical outputs of industries and wage payments.

In the pollution abatement column industry inputs of ordinary goods in various pollution-eliminating activities are recorded (z_{13} and z_{23}), along with the payments by pollution abatement activities to labour and other primary inputs (m_3). The sum $z_{13} + z_{23} + m_3$ thus records the total amount spent by the pollution abatement industry on eliminating the quantity of pollutants recorded in z_{33}. From this information, it is then possible to determine

the cost of eliminating each unit of pollutant, i.e. $\frac{z_{33}}{z_{13} + z_{23} + m_3}$. Furthermore, using matrix inversion it is also possible to derive a matrix of interdependence coefficients that enable the calculation of pollution generated given any change in final demand.

A.3.2 Commodity by Industry Input Output Approaches

Incorporating environmental-economy interactions into a standard Leontief IO is often difficult due to the following assumptions inherent in the model: (1) single product industries (or at least the aggregation of multiple outputs into one homogenous product), and (2) the need to assign market prices to all industry outputs (Lonergan and Cocklin, 1985). For this reason, and to enable easier data collection and flexibility of model design, environmental IO models have been developed from a commodity-by-industry, rather than an industry-by-industry, basis. This format enables multiple commodities to be produced by a single industry and the number of commodities and industries to differ.

Ignoring any environmental dimension, a very basic commodity-by-industry IO table is laid out in Figure A.6 below:

		Commodities	Industries	Final Demand	Totals
		$1 \ldots n$	$1 \ldots m$	$1 \ldots f$	
Commodities	$1 \ldots n$		**A**	**B**	**c**
Industries	$1 \ldots m$	**D**			**e**
Primary Inputs	$1 \ldots p$		**H**	**K**	**l**
Totals		**c**	**e**	**o**	

Figure A.6 Commodity by Industry Input-Output Framework

Source: Adapted from Victor (1972).

The 'Use matrix', **A**, in the above table describes the inputs into each of the industries listed at the head of the columns, the 'Supply matrix', **D**, shows the outputs of each of the industries in terms of commodities. This approach differs from the standard IO in that the inputs and

outputs are recorded in commodities, rather than as transfers between industries. As with the standard IO is still possible to generate both technical and independence coefficients.

The Isard Model, 1968

Isard's (1968) model has a basic structure similar to that of the Daly model (Figure A.7). Isard however employed an industry-by-commodity framework. Isard conceptualised the ecological system as a large set of independent processes involving numerous commodities. Not only do these processes provide each other with inputs, they also deliver inputs to the economic system. The economic system, in return, delivers varies commodities to the ecological system. Thus, the economic and ecological systems are inextricably interconnected.

		Economic Activities					Ecologic Processes			
		Agri-culture	Textile	…	Petroleum Refining	… Sport Fishing	Plankton Prod-uction	Herring Prod-uction	…	Cod Prod-uction
Economic Commodities	Wheat Cloth … Crude Oil	*Quadrant I* Economic System: Intersector Coefficients					*Quadrant II* Ecological Processes: Their input and output coefficients Re: Economic Comodities			
Ecologic Commodities	Water Intake Alkalinity Detritus … Plankton Herring Cod	*Quadrant III* Economic Sectors: Their input and output coefficients Re: Ecologic commodities					*Quadrant IV* Ecologic System: Interprocess Coefficients			

Figure A.7 The Isard Model

Source: Adapted from Isard (1968).

The entries for each of the quadrants are in the form of coefficients with negative values representing inputs and positive values representing outputs. Quadrant I coefficients are in the form of a dollar's worth of per dollar of output for each economic industry, while Quadrant IV coefficients record the relationship between ecological processes and ecological commodities. Quadrant III coefficients are expressed in various mass and energy units in

terms of the ecological input to, or output from, the economic system per dollar of economic output. Similarly, the Quadrant II coefficients are expressed as dollars' worth of economic commodity per unit of production by ecological processes. One of the major criticisms towards Isard's model is that the data required to complete these coefficients is not generally available.

The Victor Model, 1972

The Victor model (1972) is similar to the SUT framework (Figure A.8). It however includes a number of additional matrices and vectors to account for environmental-economic interactions. There are several salient features of the Victor Model. Firstly, the model records separately the inputs of outputs of commodities within the economy along with commodity exchanges between the economy and the environment. Matrix $\mathbf{D}$, for example, describes the output of economic commodities by industries, and matrix $\mathbf{F}$ the output of ecological commodities by industries. Similarly, matrix $\mathbf{G}$ shows the output of ecological commodities discharged from consumption of economic commodities. Secondly, entries for the ecological sector are measured in appropriate physical units, while those of the economic sector are in monetary terms. Finally, Victor uses the law of the conservation of mass to derive key accounting identities. For example, he assumes that all material flows into industry are in the first instance ecologic commodities. The mass of the outputs from industries (i.e. capital accumulation, consumer goods and waste products) must be equal to the mass of ecological commodities used as industrial inputs if the law of conservation of mass is to be satisfied. Recognising the data constraints of Isard's Quadrant IV, Victor excluded the ecological interprocess matrix from his model.

			Economic Commodities	Industries	Final Demand	Totals	Ecological Commodities		
							Land	Air	Water
			$1 \ldots n$	$1 \ldots m$	$1 \ldots f$		$n+1 \ldots t$	$t+1 \ldots v$	$v+1 \ldots z$
Economic Commodities		$1 \ldots n$		**A**	**B**	**c**		**G**	
Industries		$1 \ldots m$	**D**			**e**		**F**	
Primary Inputs		$1 \ldots p$		**H**	**K**	**l**			
Totals			**c'**	**e'**	**o'**	**p**		**q'**	
Ecological Commodities	Land	$n+1 \ldots t$	**S**	**R**		**t**			
	Air	$t+1 \ldots v$							
	Water	$v+1 \ldots z$							

Figure A.8 The Victor Model

Source: Victor (1972).

A.4 Physical Input-Output Modelling

PIOTs describes the flow of physical quantities within the economic system and between the economic system and the natural environment. They are distinguished from standard IO models, and the environmental IO models described above, in that all flows including those within the economic subsystem are recorded in mass or energy terms. PIOTs also record, unlike national accounting and input-output practices, the vast number of material flows that occur *between* the economy and environment. PIOTs have been constructed for *inter alia* Germany (Stahmer, Kuhn and Braun, 1996), Denmark (Gravgård-Pedersen, 1999), Italy (Nebbia, 1999) and New Zealand (McDonald, 2005).

PIOTs are based on the concepts of material and energy balance (Stahmer, Kuhn and Braun, 1996; Strassert, 2000). That is, since matter (and energy) can be neither created nor destroyed, all inputs into a system must equal the sum of all the outputs. PIOTs illustrate that economies exist within the finite environment by importing low-entropy matter-energy (raw materials) and exporting high entropy matter energy (waste) (Strassert, 2000). The format of a typical PIOT model is shown in Figure A.9 below.

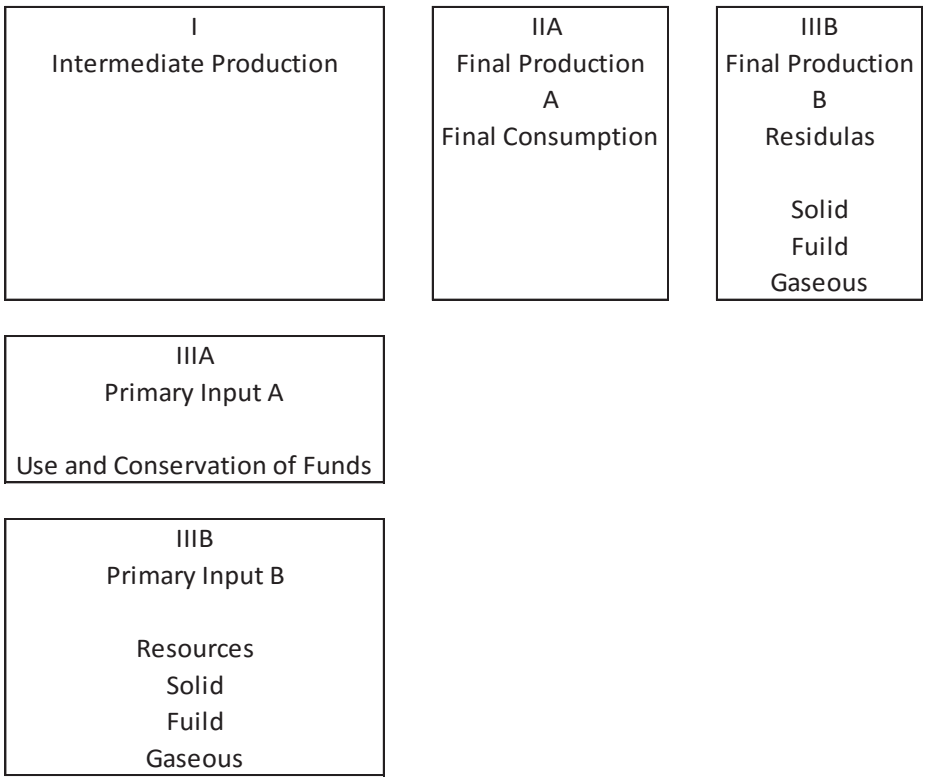

Figure A.9 A Physical Input-Output Model

Source: Adapted from Strassert (2000).

The part of the PIOT that describes flows within the economy is similar to a standard IO except with flows recorded in physical terms. Another important point of departure is the integration of the environment into the model as a source of raw materials, and as a sink for residuals. Matrix IIB, for example, records the outputs of materials/residuals from the environment to the economy, while matrix IIIB records the inputs of material resources from the environment to the economy. The flows of materials within the environment itself are omitted. In a PIOT, households are treated in an analogous manner to industries as the transformation of matter function does not differ from firms, and may be included in the transaction matrix as a quasi-production activity (Strassert, 2000).

Key limitations of PIOTs include:

- *Quality aspects*. PIOTs do not account for qualitative aspects of materials flows, e.g. poisonous and innocuous materials are measured only by their weights but not according to their impact (Stahmer, 2000).
- *Flows not stocks*. PIOTs, as with all IOs, tell us only about flows of materials and not stocks. The damage inflicted by residuals however often increases non-linearly with the amount of residual generated.
- *Donor and Receiving Environments.* While PIOTs inform us on the industrial metabolism of an economy they provide very little information on the donor environments from which raw materials are sourced, or the receiving environments to which residuals are expelled. Such inform is critical to assessment the extent of impact to the environment.
- *Ecosystem services*. PIOTs generally do not account for ecosystem services provided by the environment that are critical for life support, unless there is a measurable flow of mass/energy to or from the economic system.

Appendix B

Estimation of Symmetric Input-Output Tables[225,226]

B.1 Introduction

With the now widespread availability of high-speed digital computers, IO analysis has grown to become one of the most extensively utilised tools in applied economics (Baumol, 2000; Miller and Blair, 2009). The applications of, as well as the extensions to, the IO model are vast. The approach is now routinely applied in the study of employment effects, analysis of interdependence structures and environmental impact assessment, to name but a few applications. The United Nations itself promotes IO as a practical planning tool, and sponsors a standardized system of economic accounts for constructing IO tables (United Nations, 1993, 1999).

Despite the significant popularity achieved in the use of IO analysis, practitioners the world over cite limitations in data availability as one of the major obstacles to the application of the approach (refer to, for example, Matthews and Lave (2003), Hy and Wollscheid (2008) and Shrestha (2008)). It is because of the laborious data collection and computation procedures required for the construction of IO accounts, that the accounts are typically available at a national level only. For many countries, the accounts are also produced long after the year the data was collected, and often infrequently. In New Zealand, for example, the latest release of a symmetrical industry-by-industry table occurred in 2001, and for data applicable to the 1995-96 financial year.

Another trend noticeable among national statistical agencies has been a focus on the production of commodity-by-industry formulations of IO accounts, or SUTs, rather than SIOTs

[225] This chapter is published in the journal *Economic Systems Research*. To ensure compatibility with the mathematical framework presented in Chapter 3, Figure 3.4, minor notation changes have been made. The citation for the publication is Smith, N. J., & McDonald, G. W. (2011). Estimation of Symmetric Input-Output Tables: An Extension to Bohlin and Widell. *Economic Systems Research*, 23(1), 49-72.

[226] The models put forward in this chapter provide the necessary methods for translating data presented in process-by-commodity accounts as per Chapter 3, into commodity-by-commodity accounts as required for Chapter 6, as well as industry-by-industry accounts, as required by Chapters 8 and 10.

(Miller and Blair, 2009). The term 'symmetric' is used here to denote that the same classification (i.e. the same industry or product set) is used in both rows and columns. As it is SIOTs that are most frequently relied on for analytical purposes, this trend has only accentuated the demand placed on IO practitioners to devise methods for the estimation of IO accounts.

In their 2006 paper published in the journal *Ecosystem System Research*, Bohlin and Widell developed an optimisation model for the estimation of SIOTs, based on data contained within SUTs. A key contribution brought about by this model is that it makes possible the estimation of SIOTs, even when the underlying SUTs are rectangular. Their method furthermore addresses the problem of negative coefficients, which is a long-standing issue encountered in the derivation of SIOTs.[227] It is, however, important to note that SIOTs are in general divided into two subgroups, industry-by-industry and commodity-by-commodity, and that the model presented by Bohlin and Widell can only be used to produce the latter type.

This appendix puts forward a number of extensions to the Bohlin and Widell model. In terms of the first major extension, it is noted that a key limitation of the Bohlin and Widell model is that it does not necessarily produce balanced tables, in the sense that the total cost in the production of a commodity is equal to the value of that commodity sold (i.e. table row totals do not equate with corresponding column totals). Given that balanced tables are a logical requirement of the IO framework, it has been necessary to develop a revision of the Bohlin and Widell method to address this issue. Another significant contribution presented by this appendix is the re-specification of the technology assumptions relied on in the construction of a commodity-by-commodity SIOT. This re-specification brings the technology assumptions into closer alignment with their traditional formulation, and also means that they are significantly easier to apply in practice. Additionally this appendix provides a method for the estimation of industry-by-industry SIOTs, which is analogous to the method described here for estimating commodity-by-commodity SIOTs. Finally, this appendix explores the development of a 'comprehensive model' for the estimation of both commodity-by-commodity and industry-by-industry SIOTs.

[227] A primary reason for the production of negative coefficients is heterogeneity in the underlying data. In practice such heterogeneity is unavoidable due to the need to aggregate a vast range of economic activities and products into a set of industry and commodity groups. For a further discussion of negative coefficients arising in relation to the generation of SIOTs, reference can be made to Almon (1970), Steenge (1990) and Miller and Blair (2009).

B.2 Estimation of Symmetric Input-Output Tables

Chapter XV in the United Nations 1993 System of National Accounts is devoted to the specification of a framework for national SUTs. SUTs are described as the coordinating structure for economic statistics; ensuring the consistency of data and definitions used, and providing a comprehensive picture of the production sphere. The United Nations 1993 System of National Accounts does, however, also acknowledge the importance of SIOTs, particularly in terms of their use as a well-established tool for analytical purposes (e.g. socio-economic and environmental impact assessment). Given that many statistical agencies now concentrate on producing only SUTs, it is very common for IO practitioners to have to rely on SIOTs that are estimated from SUTs when undertaking analytical applications.

Two alternative technology assumptions are typically utilised in compiling SIOTs from SUTs: (1) the industry technology assumption (ITA), which assumes that all products produced by an industry are produced with the same input structure; and (2) the commodity technology assumption (CTA) which assumes that a product has the same input structure in whichever industry it is produced.[228] Although the CTA is often favoured from a theoretical viewpoint (Kop Jansen and ten Raa, 1990; United Nations, 1993; ten Raa and Rueda-Cantuche, 2003), application of this assumption may result in the production of negative coefficients, which are clearly nonsensical from an economic point of view. A second drawback of the CTA is that, according to its standard formulation, it is only applied in the case of square SUTs (i.e. SUTs with the same number of industries and products).

An important point that is not made clear in the United Nations 1993 System of National Accounts, and indeed is not clear in the vast majority of introductory IO texts, is that the CTA and ITA assumptions are, strictly speaking, only relevant to the creation of commodity-by-commodity SIOTs. The Eurostat IO manual (Eurostat, 2008) notes that, whereas the transformation of SUTs to commodity-by-commodity SIOTs relies on technology assumptions, the transformation of SUTs to industry-by-industry tables relies on sales structure assumptions. The manual therefore correctly states that it is inappropriate to term the latter assumptions 'industry-by-industry variants' of the CTA and ITA.

[228] Although note that ten Raa and Rueda-Cantuche (2007) put forward evidence that the commodity and industry technology models are just two particular cases of a more generalised form.

In this appendix, the terms 'fixed commodity sales structure' (FCS) and 'fixed industry sales structure' (FIS) are used to describe two alternative assumptions that can be used to translate SUTs to industry-by-industry IO tables. According to the FIS assumption, each industry has its own specific sales structure, irrespective of its product mix. As an example, say industry 1 produces two types of commodities, commodity 1 and commodity 2, and 20 percent of the output of commodity 1 is sold to industry 2. If the FIS assumption were to hold true, then 20 percent of the output of commodity 2 would also be sold to industry 2. In practical terms, it is likely that there will be relatively few situations where firms will supply all of their products in the same proportions to their users. There may be some examples in secondary trade activities, e.g. software and computers sold together by a computer producing firm.

As an alternative to the FIS assumption, the FCS assumption holds that each product has its own specific sales structure irrespective of the industry where it is produced. This means, for example, that if commodity 1 is produced in both industries 1 and 3, and industry 1 supplies 50 percent of its total output of commodity 1 to industry 2, industry 3 will also supply 50 percent of its total output of commodity 1 to industry 2. This is the most commonly utilised assumption for the generation of industry-by-industry tables (refer to Rueda-Cantuche and ten Raa (2009a)). It is also sometimes referred to as the 'market share' assumption because it ensures that the proportion of a particular commodity purchased from a selected industry will always be equal to that industry's share of the total market supply of that commodity.

In addition to the ITA, CTA, FIS and FCS assumptions, the literature puts forward a number of other approaches for the transformation of SUTs to SIOTs. For the most part these approaches relate to the production of commodity-by-commodity tables. The Stone (1961) method, for example, involves the removal of all secondary products from the supply table by treating these outputs as negative inputs in the industry where they are produced. Importantly, where the use of a particular commodity in an industry is less than the secondary output of that commodity in the same industry, the Stone method will produce a negative value in the symmetric table. As with other methods that concentrate on the removal of outputs in the supply table (refer to, for example, Eurostat (1979)), the Stone method is primarily a statistical device providing a simple means of converting to a symmetric table, albeit subject to limitations in terms of the results that are produced.[229]

[229] Reference can be made to Stahmer (1985) and Viet (1994) for a discussion of the different methods for constructing IO tables and the associated consequences and limitations of each method.

There is another set of methods for the generation of SIOTs which are termed 'hybrid approaches' (refer to Gigantes (1970), Armstrong (1975) and Rueda-Cantuche and ten Raa (2009b)). The term 'hybrid' is given to reflect a combined or mixed use of the technology assumptions. Common limitations to the use of such approaches are that they still frequently produce negative values, and typically require the use of square SUTs as a starting point.

B.2.1 A Minimisation Approach to the Estimation of Commodity-by-Commodity Tables

The method put forward by Bohlin and Widell (2006) is a hybrid approach to the estimation of commodity-by-commodity SIOTs, incorporating a novel application of optimisation techniques. Their method is essentially based around the estimation of so-called b-coefficients, or $b_{ii'j}$s, which define the quantity of commodity i that is used for producing one unit of commodity i' in industry j. These coefficients are distinct from 'ordinary' technical coefficients, $a_{ii'}$, which define for the economy as a whole, the quantity of commodity i used in the production of one unit of commodity i'. Of course, ordinary $a_{ii'}$ coefficients can be calculated once the $b_{ii'j}$ coefficients are defined, as can all the cell values necessary for the SIOT. In terms of the latter, the total quantity of commodity i used for producing commodity i', $z_{ii'}$, must be equal to the sum of the use of commodity i that is required for the production of output i' in all industries producing output i', i.e.

$$z_{ii'} \equiv \sum_{j=1}^{K} b_{ii'j} v_{ji'} ,$$

where $v_{ji'}$ is the total supply of commodity i' by industry j as defined from the supply table. The $a_{ii'}$ coefficients can then be obtained by dividing $z_{ii'}$ by the i'th column sum.

According to the Bohlin and Widell approach, the $b_{ii'j}$ coefficients are estimated by minimising the variance between selected $b_{ii'j}$s, taking account of the weights that are given to each of the CTA and ITA assumptions. Bohlin and Widell devise the minimisation problem by first reasoning that if the CTA assumption is to hold true, the same mix of inputs will be used for producing a specific product in all industries that are producing that product. In other words, for all combinations of i, i' and j,

$$b_{ii'j} = a_{ii'} .$$

If, however, the requirement that all $b_{ii'j}$ coefficients are equal is relaxed, and instead replaced with a goal of minimising the variance between the input coefficients of industries producing the same product, the CTA assumption can be replaced with the problem,

$$\text{Minimize}\left(\sum_{i'=1}^{\Psi}\text{var}\left(b_{ii'}\right)\right),$$

where var($b_{ii'}$) is the variance of the coefficients $b_{ii'j}$ in the use of commodity i for the production of commodity i' in all industries that produce commodity i'.

Importantly, this use of a minimisation approach to the application of the CTA enables the addition of a constraint requiring all coefficients to be greater than zero, thereby eliminating the problem of negative coefficients normally encountered with the use of the CTA. An additional advantage of the minimization approach is that does not require the use of square SUTs.

With respect to the ITA, Bohlin and Widell reason further that if this assumption is to hold true, an industry will experience for a selected input i, the same $b_{ii'j}$ coefficient no matter which commodity i' is being produced. The ITA assumption applied to input i can thus be reformulated as the minimization problem,

$$\text{Minimize}\left(\sum_{j=1}^{\sigma}\text{var}\left(b_{ij}\right)\right),$$

where var(b_{ij}) is, for all outputs i' that are produced in industry j, the variance of the $b_{ii'j}$s in that industry for the use of input i.

Both the CTA and ITA minimisation problems are, of course, subject to a constraint that the total quantity of input i used in industry j must be equal to the sum of the use of commodity i in the production of all commodities that are produced by industry j. In equation form,

$$u_{ij} \equiv \sum_{i'=1}^{\Psi} b_{ii'j} v_{ji'}\,, \qquad \text{(B.1)}$$

where $u_{ij'}$ is the total quantity of input i used in industry j' as defined from the use table.

Putting the above formulations together, Bohlin and Widell devise a method for calculating commodity-by-commodity SIOTs, utilising a combination of the CTA and ITA assumptions. This method is expressed as the following minimization problem for commodity input i:

$$\begin{aligned} &\text{Minimize}\left(\mu_i \sum_{i'=1}^{\psi} \text{var}(b_{ii'}) + \omega_i \sum_{j=1}^{\sigma} \text{var}\left(b_{ij}\right) \right) \\ &\text{subject to } b_{ii'j} \geq 0 \text{ and } u_{ij} = \sum_{i'=1}^{\psi} b_{ii'j} v_{ji'} \end{aligned} \quad . \qquad \text{(B.2)}$$

The terms μ_i and ω_i are, for commodity input i, the weights given to the CTA and ITA respectively. The relative size of these weights is determined by the relative importance put on CTA and ITA assumptions for commodity i. Taking, for example, a given commodity i, if μ_i = 5000 and ω_i = 0, then this means that full weight is given to the CTA assumption for commodity i in the optimisation problem. If, however, the weights were to instead, say, be set as μ_i = 2500 and ω_i = 2500, the CTA and ITA assumptions would be equally applied to commodity i. Note that Bohlin and Widell do not put any restriction on the size of these weights, since the value of the objective function is not important, only the resulting b-coefficients. In the application section that follows, the sum of the two weights for any given commodity is always set to a value of 5000, although alternative values could also have been chosen.

Extension 1: Removing Bias in the Bohlin and Widell Model

The first extension that is proposed to the Bohlin and Widell model is relatively minor, and involves the addition of two denominators, $\tilde{\psi}_i$ and $\tilde{\sigma}_i$, to the ITA and CTA weights respectively. The term $\tilde{\psi}_i$ represents the total number of i' commodities produced by all industries receiving inputs of commodity i, while $\tilde{\sigma}_i$ represents the total number of j industries receiving inputs of commodity i. The revised model for estimating commodity-by-commodity SIOTs is therefore:

$$\text{Minimize}\left(\mu_i \frac{\sum_{i'=1}^{\psi} \text{var}(b_{ii'})}{\tilde{\psi}_i} + \omega_i \frac{\sum_{j=1}^{\sigma} \text{var}\left(b_{ij}\right)}{\tilde{\sigma}_i} \right).$$

$$\text{subject to } b_{ii'j} \geq 0 \text{ and } u_{ij} = \sum_{i'=1}^{\psi} b_{ii'j} v_{ji'}$$

The two denominators are added to the objective function to ensure that the optimal result is not overtly influenced by differences in the number of industries and commodities in the SUTs. To explain, take for example a situation where equal weight is to be given to the CTA and ITA for commodity input i (e.g. μ_i=2500 and ω_i=2500), and in this situation there are also 20 different industries receiving inputs of commodity i for the production of 30 different commodity types. If the terms $\tilde{\psi}_i$ and $\tilde{\sigma}_i$ were not added, the CTA variances would have a greater impact on the objective function than the ITA variances given that they must be summed across all 30 commodity types whereas the ITA variances are only summed across 20 industry types.

Extension 2: Producing a Balanced Commodity-by Commodity Symmetric Input-Output Table

According to the Bohlin and Widell model, the minimisation problem (Eq. B.2) is calculated separately for each input i, or in other words for each row of the SIOT. There is, however, a fundamental problem with dividing the problem in this way. That is, although it may be mathematically feasible to generate b-coefficients in a sequential process for each input i, the b-coefficients found will not necessarily produce a balanced SIOT.

Before pursuing this problem further, it is worth noting that if the ITA assumption is applied to all inputs in the Bohlin and Widell model, this is a special case where the solution should generate a balanced table. The reason is that under the ITA solution, the proportion of commodity i inputs to industry j that are allocated to the production of commodity i', is always equivalent to the proportion of industry j's total outputs that are made up of commodity i', i.e.

$$z_{ii'j} = u_{ij} \frac{v_{ji'}}{\sum_{i'=1}^{\sigma} v_{ji'}} \quad ,$$

where $z_{ii'j}$ is the use of commodity i in the production of commodity i' by industry j, and all other terms are as defined above. It therefore follows that when the ITA is applied to all

commodity and primary inputs, the total inputs required for the production of commodity i' summed across all j industries, $\alpha_{i'}$, can be calculated as,

$$\alpha_{i'} = \left(\sum_{i=1}^{\psi} u_{i1} + p_1\right)\frac{v_{1i'}}{\sum_{i'=1}^{\psi} v_{1i'}} + \left(\sum_{i=1}^{\psi} u_{i2} + p_2\right)\frac{v_{2i'}}{\sum_{i'=1}^{\psi} v_{2i'}} \ldots + \left(\sum_{i=1}^{\psi} u_{i\sigma} + p_\sigma\right)\frac{v_{\sigma i'}}{\sum_{i'=1}^{\psi} v_{\sigma i'}},$$

where $p_{j'}$ is the total primary inputs required by industry j ($j \in \{1 \ldots \sigma\}$). Assuming the underlying SUTs from which the data are derived are balanced, with total inputs equivalent to total outputs for each industry, it is now possible to cancel-out numerators and denominators in the above equation leaving simply:

$$\alpha_{i'} = v_{1i'} + v_{2i'} \ldots + v_{\sigma i'}.$$

This shows that applying the ITA assumption, the commodity-by-commodity table produced from the Bohlin and Widell model must be in balance, with the total inputs required for the production of commodity i' being equivalent to the total supply of commodity i' by all j industries.

If the CTA is applied to all inputs under the Bohlin and Widell model, it is also possible that a balanced table will be produced. There are, however, a number of special features of the CTA that reduce the likelihood of obtaining a balanced table. To explain, recall from above that the CTA entails that for any selected input i and output i', the coefficient $b_{ii'j}$ is equivalent across all k industries. Now, letting $b^*_{ii'}$ denote the constant input coefficient for commodity i in the production of commodity i', it is possible to devise a set of simultaneous equations based on the constraint specified in Eq. B.1 above for the use of commodity i by each of the j industries:

$$\begin{aligned}
&b^*_{i1}v_{11} + b^*_{i2}v_{12} + b^*_{i3}v_{13} \ldots b^*_{i\psi}v_{1\psi} = u_{i1} \\
&b^*_{i1}v_{21} + b^*_{i2}v_{22} + b^*_{i3}v_{23} \ldots b^*_{i\psi}v_{2\psi} = u_{i2} \\
&b^*_{i1}v_{31} + b^*_{i2}v_{32} + b^*_{i3}v_{33} \ldots b^*_{i\psi}v_{3\psi} = u_{i3} \quad . \\
&\vdots \\
&b^*_{i1}v_{\sigma 1} + b^*_{i2}v_{\sigma 2} + b^*_{i3}v_{\sigma 3} \ldots b^*_{i\psi}v_{\sigma\psi} = u_{i\sigma}
\end{aligned}$$

In matrix notation these simultaneous equations can be written as,

$$\mathbf{B}^{*}\mathbf{V}^{\mathrm{T}} = \mathbf{U}.$$

Now, provided that $\mathbf{V}$ is square and non-singular, the unknown b^* coefficients which satisfy the CTA assumption for commodity inputs i can be determined according to the equation:

$$\mathbf{B}^{*} = \mathbf{U}\left(\mathbf{V}^{\mathrm{T}}\right)^{-1}.$$

If the matrix $\mathbf{B}^*$ can be solved for every input i, the Bohlin and Widell model will produce a balanced commodity-by-commodity table. In practice this is, however, likely to occur relatively infrequently because, not only are the $\mathbf{V}$ matrices often unable to be inverted, the Bohlin and Widell model includes the additional constraint that the solution must contain no negative elements.

In this appendix, the Bohlin and Widell model is extended to ensure that balanced tables will be produced under any arrangement of the CTA and ITA assumptions. This involves first including all the b-coefficients (i.e. every combination of i, i' and j) in a single minimisation problem, and second reducing the solution space for the problem by adding a constraint that requires row and column balance in the SIOT.

Following the normal structure of an IO table, row and column balance is achieved where the total value of all inputs to a production activity, is equal to the total value of outputs for that production activity. For the production of commodity i' by industry j, this requirement is specified in the equivalence,

$$v_{ji'} \equiv \sum_{i=1}^{\psi} b_{ii'j} v_{ji'} + \sum_{h=1}^{\phi} p_{hi'j}\ , \qquad \text{(B.3)}$$

where $p_{hi'j}$ is the value of primary input h used by industry j in the production of commodity i', and the other terms are as defined above.[230] The minimisation problem incorporating Eq. B.3 is therefore,

[230] For simplicity, it is assumed that there are no independent trade taxes (vector $\mathbf{x}^{t}$ in Figure 3.4 in Chapter 3) levied on commodity i'.

$$\text{Minimize}\left(\sum_{i=1}^{\psi}\left(\mu_i\frac{\sum_{i'=1}^{\psi}\text{var}(b_{ii'})}{\tilde{\psi}_i}+\omega_i\frac{\sum_{j=1}^{\sigma}\text{var}\left(b_{ij}\right)}{\tilde{\sigma}_i}\right)\right), \qquad \text{(B.4)}$$

$$\text{subject to } b_{ii'j}\geq 0\ ,\ u_{ij}=\sum_{i'=1}^{\psi}b_{ii'j}v_{ji'} \text{ and } v_{ji'}=\sum_{i=1}^{\psi}b_{ii'j}v_{ji'}+\sum_{h=1}^{\phi}p_{hi'j}$$

with the number of unknown variables being the number of $b_{ii'j}$ coefficients.

This reformulation of the optimisation problem assumes that there will be data available on the primary inputs required for the production of each commodity (i.e. the vectors of $p_{hi'j}$s). In practice, however, because of the way in which SUTs are compiled, primary inputs data is often only available at an industry level – typically the total value of different primary inputs received by each industry. This means that in order to compile a commodity-by-commodity SIOT it will be necessary, just as with commodity inputs, to allocate the primary inputs received by each industry to the different commodities each industry produces. If a practitioner does not wish to independently undertake this task, the primary inputs data for commodities can be estimated as part of the optimisation model. This approach requires estimating primary inputs according to the same manner in which the b-coefficients are estimated for commodity inputs. The primary input coefficient, $c_{hi'j}$, for the use of primary input h in the production of commodity i' by industry j is defined as:

$$c_{hi'j}=\frac{p_{hi'j}}{v_{ji'}}\ .$$

When these c-coefficients are incorporated into Eq. B.4, the optimisation problem becomes,

$$\text{Minimize}\left(\sum_{i=1}^{\psi}\left(\mu_i\frac{\sum_{i'=1}^{\psi}\text{var}(b_{ii'})}{\tilde{\psi}_i}+\omega_i\frac{\sum_{j=1}^{\sigma}\text{var}\left(b_{ij}\right)}{\tilde{\sigma}_i}\right)+\sum_{h-1}^{\phi}\left(\mu_h\frac{\sum_{i'=1}^{\psi}\text{var}(c_{hi'})}{\tilde{\psi}_h}+\omega_h\frac{\sum_{j=1}^{\sigma}\text{var}\left(c_{hj}\right)}{\tilde{\sigma}_h}\right)\right), \qquad \text{(B.5)}$$

$$\text{subject to } b_{ii'j}\geq 0\ ,\ u_{ij}=\sum_{i'=1}^{\psi}b_{ii'j}v_{ji'},\ p_{hj}=\sum_{i'=1}^{\psi}c_{hi'j}v_{ji'} \text{ and } v_{ji'}=\sum_{i=1}^{\psi}b_{ii'j}v_{ji'}+\sum_{h=1}^{\phi}c_{hi'j}v_{ji'}$$

with the number of unknown variables now equivalent to the number of b-coefficients plus the number of c-coefficients. Analogous to the variances used in the case of commodity

inputs, var($c_{hi'}$) represents the variance in the $c_{hi'j}$ coefficients across all j industries receiving primary input h and producing commodity i', while var(c_{hj}) is the variance in the $c_{hi'j}$ coefficients for primary input h across all i' commodities produced by industry j. Similarly $\tilde{\psi}_h$ is the total number of i' commodities produced by all industries receiving primary input h and $\tilde{\sigma}_h$ is the total number of j industries receiving primary input h. Lastly, μ_h is the weight given to the CTA for primary input h and ω_h is the weight given to the ITA for primary input h.

Like the original Bohlin and Widell model, the above reformulation of the optimisation problem (either Eq. B.4 or B.5) enables commodity-by-commodity SIOTs to be calculated based on industry and commodity data contained within SUTs. The important difference is that the new approach ensures that the SIOTs will balance. The drawback of the method is that, because of the need to solve the minimization problem for all industries, inputs and outputs simultaneously, the formulation extends the size of the optimisation problem, and thus the computing resources required for its solution. Variables and constraints are discussed further in Section B.4.

Extension 3: Improving the Application of the Technology Assumptions

The optimisation problem thus far formulated requires for each commodity input i (and primary inputs if included in the problem), a decision as to the appropriate weights to be given to both the CTA and ITA assumptions. It is argued that this is not the best approach to the application of the technology assumptions. Instead, the allocation of weights to the CTA and ITA assumptions should occur for each commodity output i'.

To illustrate the above point, a hypothetical example is provided of a simple economy, where the commodity fertiliser is used as an input in both the dairy cattle farming and horticulture industries. In this example, the dairy cattle farming industry is also responsible for the production of both beef and milk products, while the horticulture industry produces fruit and a small amount of beef products. The components of the three-dimensional b-coefficient matrix which describe this situation are depicted by the two matrices found in Tables B.1 and B.2.

Table B.1 Use of Fertiliser Inputs by Dairy Cattle Farming (Industry 1)

Input (i) \ Output (j)	Commodity 1 (beef)	Commodity 2 (milk)
Commodity 1 (fertilizer)	b_{111}	b_{121}

Table B.2 Use of Fertiliser Inputs by Horticulture (Industry 2)

Input (i) \ Output (j)	Commodity 1 (beef)	Commodity 3 (fruit)
Commodity 1 (fertilizer)	b_{112}	b_{132}

According to the minimisation problem thus far put forward, it is necessary to consider whether for the fertiliser commodity, it is appropriate to place more (or equal) weight on the CTA or the ITA. If we start with products produced by dairy cattle farming, it is reasonable to assume that the ITA is the more appropriate assumption for fertiliser inputs (i.e. the variance between the coefficients b_{111} and b_{121} is equal to or near zero). This is because beef is likely to be produced as a by-product of milk production, and therefore requires the same input mix of fertiliser for every unit of beef production as that of milk. But now, because the minimisation problem as specified in Eqs. B.2 and B.4 requires that the weight given to a technology assumption for a given commodity i is to be applied in every situation where that commodity is used as an input, the ITA assumption must also be applied to the case of fertiliser inputs into horticulture. Equally, the assumption must also be applied to every other situation where fertiliser is used as an input in an industry's production. At least, with respect to horticulture production, it is unlikely that the ITA is the most appropriate assumption. In the horticulture industry beef is more likely to be an example of a subsidiary product, where production occurs according to an entirely different technology mix to that of the main product (i.e. fruit), thereby requiring a different input ratio for fertiliser.

With the above example in mind, it can be observed that it is more appropriate to allocate weights to the two technology assumptions for each output j rather than for each input i. This occurs because the ITA and CTA are, by their very nature, assumptions around the outputs of

production processes. It is further argued that it is significantly easier to decide on CTA and ITA weights for each commodity produced by each individual industry, rather than for each commodity produced by the economy as a whole. This approach avoids the need to consider all production activities producing a given commodity at once, and somehow select weights that represents these activities as an aggregate. The following equation provides a formulation of the minimisation problem specified in Eq. B.4, where the CTA and ITA weights are allocated for each commodity output produced by each industry:

$$\begin{aligned} &\text{Minimize}\left(\sum_{i'=1}^{\psi} \sum_{j=1}^{\sigma} \left(\mu_{i'j} \sum_{i=1}^{\psi_{i'}} \text{var}(b_{ii'}) + \omega_{i'j} \sum_{i=1}^{\psi_j} \text{var}\left(b_{ij}\right) \right) \right) \\ &\text{subject to } b_{ii'j} \geq 0 \text{ , } u_{ij} = \sum_{i'=1}^{\psi} b_{ii'j} v_{ji'} \text{ and } v_{ji'} = \sum_{i=1}^{\psi} b_{ii'j} v_{ji'} + \sum_{h=1}^{\phi} p_{hi'j} \end{aligned} \quad . \qquad \text{(B.6)}$$

Note that the set $i = \{1, \ldots \psi_{i'}\}$ is comprised of all commodity types purchased by any of the industries producing commodity i', while the set $i = \{1, \ldots \psi_j\}$ is comprised of all commodity types purchased by industry j. The terms $\mu_{i'j}$ and $\omega_{i'j}$ denote, for commodity output i' produced by industry j, the weights allocated to the CTA and ITA respectively, and that the remaining terms are as specified above.

In an ideal application of this model, the selection of the $\mu_{i'j}$ and $\omega_{i'j}$ weights for each commodity would be based on detailed statistical data. Such data would provide information on the extent to which, at an aggregate industry level, a given commodity produced by a given industry is produced according to the same input mix as other commodities produced by that same industry (ITA), versus the same input mix as used for the production of that commodity by other industries (CTA). Unfortunately, it is however envisaged that such data will seldom be available to practitioners, at least not for every commodity and industry. Therefore, in practice, practitioners applying this model will be most likely to draw on their own and other industry experts' judgement in setting appropriate weights, applying relevant statistical data where it may be available.

A possible method by which the information required to set the CTA and ITA weights might instead be inferred is given by ten Raa *et al*. (1984). Essentially their method involves examining the changes in output that occur for each industry across a series of SUTs. Then, based on the relative changes in output between commodities produced by each industry, the

commodity outputs are classified as primary products, secondary products or by-products. Finally, it is assumed that all commodities classified as either primary or secondary products fulfil the CTA, while for by-products the ITA is more applicable.[231] In the future it will be interesting to consider other possible methods that might be employed in setting the CTA and ITA weights.

Once again, the model can be extended to allow for the estimation of primary input coefficients where the required data on primary inputs is not otherwise available. Eq. B.6 incorporating the estimation of primary input coefficients is:

$$\text{Minimize}\left(\sum_{i'=1}^{\psi}\sum_{j=1}^{\sigma}\left(\mu_{i'j}\left(\sum_{i=1}^{\psi_{i'}}\text{var}(b_{ii'})+\sum_{h=1}^{\phi_{i'}}\text{var}(c_{hi'})\right)+\omega_{i'j}\left(\sum_{i=1}^{\psi_j}\text{var}\left(b_{ij}\right)+\sum_{h=1}^{\phi_h}\text{var}(c_{hj})\right)\right)\right). \quad \text{(B.7)}$$

$$\text{subject to } b_{ii'j}\geq 0\ ,\ u_{ij}=\sum_{i'=1}^{\psi}b_{ii'j}v_{ji'},\ p_{hj}=\sum_{i'=1}^{\psi}c_{hi'j}v_{i'j} \text{ and } v_{ji'}=\sum_{i=1}^{\psi}b_{ii'j}v_{ji'}+\sum_{h=1}^{\phi}c_{hi'j}v_{ji'}$$

Following the same approach as above, the set $h=\{1,\ldots\phi_{i'}\}$ contains all primary input types purchased by industries producing commodity i', while the set $h=\{1,\ldots\phi_j\}$ contains all primary input types purchased by industry j.

B.2.2 A Minimisation Approach to the Estimation of Industry-by-Industry Tables

In Section B.2.1, a method has been devised for the calculation of commodity-by-commodity SIOTs using an optimisation approach. Now, building on the optimisation framework set out so far, this section presents a method for estimating industry-by-industry SIOTs. The model developed is analogous to that used in the case of commodity-by-commodity SIOTs, but this time it incorporates the FCS and FIS assumptions in the minimisation problem as opposed to the CTA and ITA. Two important features of this model, as with the commodity-by-commodity model, are that it enables SIOTs to be generated utilising rectangular SUTs as a starting point, and secondly, the generation of negative coefficients is avoided.

The first step in the formulation of the minimisation problem for the industry-by-industry model is to identify a new type of coefficient, this time termed *d*-coefficients. These *d*-

[231] In fact, due to limitations associated with the ITA assumption, ten Raa *et al*. (1984) chose to apply the by-product technology model, rather than the ITA, to commodities classified as by-products.

coefficients are comparable to the b-coefficients described above, except that the d-coefficients are supply coefficients rather than use coefficients. The coefficient $d_{ijj'}$ describes, for every one unit of commodity i produced in industry j', the quantity of commodity i that is suplied to industry j. By definition, the total supply of commodity i by industry j' must be equal to the amount of that commodity supplied by industry j' to all j industries, plus commodity i supplied by industry j' to final demands. This identify, which in equation form is described as,

$$v_{ij'} \equiv \sum_{j=1}^{K} d_{ijj'} v_{j'i} + \sum_{f=1}^{\pi} y_{ifj'} \,, \tag{B.8}$$

provides a row sum constraint equivalent to that specified in Eq. B.1 for the commodity-by-commodity SIOT model. In the above equation, $v_{ij'}$ is the quantity of commodity i supplied by industry j' (as recorded in the supply table), and $y_{ifj'}$ is the total quantity of commodity i supplied by industry j' to final demand type f.[232]

In order to ensure that the industry-by-industry table created from these d-coefficients is balanced, it is also necessary to specify a column sum constraint. The appropriate constraint provides that the sum of commodity i supplied to industry j by all j' industries is equal to industry j's total use of commodity i. In equation form this is,

$$u_{ij} \equiv \sum_{j'=1}^{\sigma} d_{ijj'} v_{ij'} \,, \tag{B.9}$$

where u_{ij}, as already described above, is the use of commodity i by industry j as defined in the use table.

Having set out row and column balance constraints, the next step is to formulate expressions for the FCS and FIS assumptions that are appropriate for use in a minimisation problem. As noted above, these assumptions revolve around sales structures, or in other words, the proportions of an output of a product that are sold to purchasing industries. Beginning with the FCS assumption, it holds that each product has its own specific sales structure irrespective

[232] Note that in the static framework for this thesis (Figure 3.4 in Chapter 3) separate final demand vectors are depicted for each of households ($\mathbf{y}^{o}$), government ($\mathbf{y}^{g}$) and capital ($\mathbf{y}^{c}$). This Chapter, however, relies on the more generic specification of a final demands matrix $\mathbf{y}$, defined by π different final demand types.

of the industry where it is produced. This is equivalent to saying that the $d_{ijj'}$ coefficients for each combination of commodity i supplied to industry j are equivalent across all j' industries. The FCS assumption applied to the supply of commodity i by industry j' can therefore be specified as a minimisation problem,

$$\text{Minimize}\left(\sum_{j=1}^{\sigma}\text{var}\left(d_{ij}\right)\right), \tag{B.10}$$

where var(d_{ij}) is, for all j' industries supplying commodity i, the variance in the d-coefficients for the supply of commodity i to industry j.

According to the FIS assumption, each industry has its own specific sales structure, irrespective of its product mix. This means that the $d_{ijj'}$ coefficients are equal across all i commodities for any combination of supplying industry j' and purchasing industry j. For commodity i produced by industry j' the FIS assumption can therefore be formulated as the problem,

$$\text{Minimize}\left(\sum_{j=1}^{\sigma}\text{var}\left(d_{jj'}\right)\right), \tag{B.11}$$

where var($d_{jj'}$) is, for all i commodities produced by industry j', the variance in the d-coefficients for the supply of commodity i to industry j.

Putting Eqs. B.8 to B.11 together, the $d_{ijj'}$ coefficients required to construct an industry-by-industry table can be calculated according to the following optimisation problem:

$$\begin{aligned}&\text{Minimize}\left(\sum_{i=1}^{\psi}\sum_{j'=1}^{\sigma}\left(\alpha_{ij'}\sum_{j=1}^{\sigma_i}\text{var}\left(d_{ij}\right)+\beta_{ij'}\sum_{j=1}^{\sigma_{j'}}\text{var}\left(d_{jj'}\right)\right)\right)\\&\text{subject to } \mathrm{d}_{ijj'}\geq 0,\ u_{ij}=\sum_{j'=1}^{\sigma}d_{ijj'}v_{j'i} \text{ and } v_{il}=\sum_{j=1}^{\sigma}d_{ijj'}v_{j'i}+\sum_{f=1}^{\pi}y_{ifj'}\end{aligned}. \tag{B.12}$$

Analogous to Eq. B.6 above, $\alpha_{ij'}$ and $\beta_{ij'}$ represent, for commodity i supplied by industry j', the weight allocated to the FCS and FIS assumptions respectively. The set $j=\{1,\ldots\sigma_i\}$ contains all industries purchasing inputs of commodity i, while the set $j=\{1,\ldots\sigma_{j'}\}$ captures industries that purchase any of the commodity types produced by industry j'.

In order to carry out the minimisation problem specified in Eq. B.12, it is necessary to use as input data, vectors of final demand sales by commodity consumed and supplying industry (the $f_{ifj'}$ variables). It is, however, quite possible, as in the case of the $p_{hi'j}$ variables, that this data will not be available from national statistical agencies. By convention, final demands are usually recorded in SUTs according to the type of commodity consumed and not by the supplying industry. One possibility is therefore to extend the FCS and FIS assumptions to allow for the estimation of these variables. The industry-by-industry model incorporating the estimation of final demand coefficients becomes,

$$\text{Minimize}\left(\sum_{i=1}^{\psi}\sum_{j'=1}^{\sigma}\left(\alpha_{ij'}\left(\sum_{j=1}^{\sigma_i}\text{var}\left(d_{ij}\right)+\sum_{f=1}^{\pi_i}\text{var}\left(e_{if}\right)\right)+\beta_{ij'}\left(\sum_{j=1}^{\sigma_{j'}}\text{var}\left(d_{jj'}\right)+\sum_{f=1}^{\pi_{j'}}\text{var}\left(e_{fj'}\right)\right)\right)\right). \quad \text{(B.13)}$$

$$\text{subject to } \mathrm{d}_{ijj'} \geq 0,\ u_{ij}=\sum_{j'=1}^{\sigma} d_{ijj'}v_{j'i},\ y_{if}=\sum_{j'=1}^{\sigma} e_{ifj'}v_{j'i} \text{ and } v_{j'i}=\sum_{j=1}^{\sigma} d_{ijj'}v_{j'i}+\sum_{f=1}^{\pi} e_{ifj'}v_{j'i}$$

The variable $e_{ifj'}$ denotes, for industry j', the supply coefficient for the sale of commodity i to final demands f, i.e.

$$e_{ifj'}=\frac{y_{ifj'}}{v_{ij'}}.$$

The var(e_{if}) refers to the variance in the $e_{ifj'}$ coefficients across all j' industries supplying commodity i to final demands f, while var ($e_{fj'}$) refers to the variance in the $e_{ifj'}$ coefficients across all i commodities supplied by industry j' to final demands f.

Finally, contained within the set $f=\{1,\ldots\pi_i\}$ are the final demand categories that purchase commodity i, while the set $f=\{1,\ldots\pi_{j'}\}$ is comprised of the final demand categories that purchase any of the commodity types produced by industry j'.

B.2.3 A Comprehensive Framework for the Estimation of Symmetric Input-Output Tables

Building on the models that are set out above, this section now put forwards a comprehensive model for the estimation of SIOTs. This model enables users to take a set of supply and use

tables, and calculate both a commodity-by-commodity table and an industry-by-industry table from a single set of assumptions.

To begin, the comprehensive model is based around the estimate of d-coefficients. These coefficients are similar to the supply coefficients used in the industry-by-industry model above except that an additional dimension, i', is added to describe the commodity that is being produced by purchasing industry j. In summary, the coefficient $d_{ii'jj'}$ describes, for every one unit of commodity i produced in industry j', the quantity of commodity i that is supplied to industry j for the production of commodity i'. Of course four-dimensional input coefficients (i.e. b-coefficients), that are similar to those used in the commodity-by-commodity model, can also be determined from the supply coefficients according to the equation,

$$b_{ii'jj'} = \frac{d_{ii'jj'} v_{j'i}}{v_{ji'}},$$

where the term $b_{ii'jj'}$ denotes, for every unit of commodity i' produced by industry j, the quantity of commodity i supplied by industry j', $v_{j'i}$ is the total production of commodity i by industry j', and vji' is the total production of commodity i' by industry j.

Now, by combining the concepts put forward in the commodity-by-commodity and industry-by-industry models, a new minimisation problem for the estimation of the unknown d-coefficients is formulated as,

$$\text{Minimize} \left(\begin{array}{c} \sum_{i'=1}^{\psi} \sum_{j=1}^{\sigma} \left(\mu_{i'j} \sum_{i=1}^{\psi_{i'}} \sum_{j'=1}^{\sigma} \text{var}\left(b_{ii'j'}\right) + \omega_{i'j} \sum_{i=1}^{\psi_j} \sum_{j'=1}^{\sigma} \text{var}\left(b_{ijj'}\right) \right) \\ \sum_{i=1}^{\psi} \sum_{j'=1}^{\sigma} \left(\alpha_{ij'} \sum_{i'=1}^{\psi} \sum_{j=1}^{\sigma_i} \text{var}\left(d_{ii'j}\right) + \beta_{ij'} \sum_{i'=1}^{\psi} \sum_{j=1}^{\sigma_{j'}} \text{var}\left(d_{i'jj'}\right) \right) \end{array} \right)$$

$$\text{subject to:} \qquad \text{(B.14)}$$

$$d_{ii'jj'} \geq 0,\ b_{ii'jj'} = \frac{d_{ii'jj'} v_{j'i}}{v_{ji'}},\ u_{ij} = \sum_{i'=1}^{\psi} \sum_{j'=1}^{\sigma} d_{ii'jj'} v_{j'i},\ v_{ji'} = \sum_{i=1}^{\psi} \sum_{j'=1}^{\sigma} d_{ii'jj'} v_{j'i} + \sum_{h=1}^{\phi} p_{hi'j}$$

$$\text{and } v_{j'i} = \sum_{i'=1}^{\psi} \sum_{j=1}^{\sigma} d_{ii'jj'} v_{j'i} + \sum_{f=1}^{\pi} y_{ifj'}$$

In the above equation, $\mu_{i'j}$ and $\omega_{i'j}$ are, once again, for commodity output i' produced by industry j, the weights allocated to the CTA and ITA. Similarly $\alpha_{ij'}$ and $\beta_{ij'}$ are, for commodity

input i supplied by industry j', the weights allocated to the FCS and FIS assumptions respectively. The four variances are as follows: (1) var($b_{ii'j'}$) is, for all j industries producing output i', the variance in the input coefficients across the industries for the use of commodity i supplied by industry j'; (2) var($b_{ijj'}$) is, for all i' commodities produced by industry j, the variance in the input coefficients for the use of commodity i supplied by industry j'; (3) var($d_{ii'j}$) is, for all j' industries supplying commodity i, the variance in the supply coefficients for the supply of that commodity to industry j for the production of commodity i'; and var($d_{i'jj'}$) is, for all i commodities produced by industry j', the variance in the supply coefficients for the supply of those commodities to industry j for the production of commodity i'. All other terms in Eq. B.14 are as already defined.

As with the commodity-by-commodity and industry-by-industry models, the comprehensive model can be reformulated to allow for the estimation of primary input coefficients and final demand sale coefficients. The extended version of the comprehensive model is:

$$\text{Minimize}\left(\begin{array}{l}\sum_{i'=1}^{\psi}\sum_{j=1}^{\sigma}\left(\mu_{i'j}\left(\sum_{i=1}^{\psi_{i'}}\sum_{j'=1}^{\sigma}\text{var}\left(b_{ii'j'}\right)+\sum_{h=1}^{\phi_{i'}}\text{var}\left(c_{hi'}\right)\right)+\omega_{i'j}\left(\sum_{i=1}^{\psi_j}\sum_{j'=1}^{\sigma}\text{var}\left(b_{ijj'}\right)+\sum_{h=1}^{\phi_j}\text{var}\left(c_{hj}\right)\right)\right)\\ \sum_{i=1}^{\psi}\sum_{j'=1}^{\sigma}\left(\alpha_{ij'}\left(\sum_{i'=1}^{\psi}\sum_{j=1}^{\sigma_i}\text{var}\left(d_{ii'j}\right)+\sum_{f=1}^{\pi_i}\text{var}\left(e_{if}\right)\right)+\beta_{ij'}\left(\sum_{i'=1}^{\psi}\sum_{j=1}^{\sigma_{j'}}\text{var}\left(d_{i'jj'}\right)+\sum_{f=1}^{\pi_{j'}}\text{var}\left(e_{fj'}\right)\right)\right)\end{array}\right). \quad \text{(B.15)}$$

subject to:

$$d_{ii'jj'}\geq 0,\ b_{ii'jj'}=\frac{d_{ii'jj'}v_{j'i}}{v_{ji'}},\ u_{ij}=\sum_{i'=1}^{\psi}\sum_{j'=1}^{\sigma}d_{ii'jj'}v_{j'i},\ p_{hj}=\sum_{i'=1}^{\psi}c_{hi'j}v_{ji'},\ y_{if}=\sum_{j'=1}^{\sigma}e_{ifj'}v_{j'i},$$

$$v_{ji'}=\sum_{i=1}^{\psi}\sum_{j'=1}^{\sigma}d_{ii'jj'}v_{ji'}+\sum_{h=1}^{\phi}c_{hi'j}v_{ji'}\ \text{and}\ v_{j'i}=\sum_{i'=1}^{\psi}\sum_{k=1}^{\sigma}d_{ii'jj'}v_{j'i}+\sum_{f=1}^{\pi}e_{ifj'}v_{j'i}$$

Once the d-coefficients are determined from the either Eq. B.14 or B.15, the elements of the commodity-by-commodity table, z_{ij} can be easily filled in according to the equation,

$$z_{ii'}=\sum_{j=1}^{\sigma}\sum_{j'=1}^{\sigma}d_{ii'jj'}v_{ij'}\ .$$

Similarly the elements of the industry-by-industry table, are calculated as,

$$z_{jj'}=\sum_{i=1}^{\psi}\sum_{i'=1}^{\psi}d_{ii'jj'}v_{ij'}\ ,$$

where $z_{jj'}$ is the output of industry j' supplied to industry j.

When comparing the comprehensive model against the commodity-by-commodity and industry-by industry models described above there are two important points to note: (1) the comprehensive model describes all intermediate production transactions in terms of four dimensions (input commodity i, producing industry j', purchasing industry j and output commodity i'), which is different from the commodity-by-commodity and industry-by-industry models which each use only three dimensions ($ii'j$ and ijj' respectively); and (2) related to point 1, in the comprehensive model the CTA, ITA, FCS and FIS assumptions are extended beyond their traditional formulations. In order to understand the way in which the assumptions are extended, take for example the ITA assumption. According to its traditional formulation, the assumption implies that the technical coefficient for inputs of a selected commodity to an industry will be the same for all products produced by that industry. In the comprehensive model, however, this assumption is extended to imply that the coefficients are not just the same for a selected commodity input, they are also the same for a selected commodity input *produced by a selected industry*. Similar extensions, which all occur because of an additional dimension, are also made with respect to the other assumptions.

Overall, because of the detailed (4-dimensional) way in which the comprehensive model interprets and categorises all economic transactions, it is likely that the model will prove most useful in applications requiring in-depth information on the nature of production activities/ and or economic outputs. IO approaches to environmental supply chain analysis are, for example, just one of a number of possible types of applications where the comprehensive model might prove useful. In these applications, IO models are used to trace the appropriation of environmental goods and services through economic production chains, thereby allowing for the environmental impacts 'embodied' in different types of economic goods to be assessed (refer to, for example, Patterson *et al*. (2010)).[233] When undertaking an environmental supply chain analysis, it is important to consider not only the types of inputs (i.e. commodities) that are required for the production of goods, but also the different production activities (i.e. industries) that might be responsible for supplying these inputs, as different production activities typically entail different environmental impacts. The comprehensive model provides a framework that allows for these dimensions of environmental supply chain analysis to be investigated, with each commodity allocated to specific producing industries. The model

[233] These applications are sometimes also referred to as 'partial life-cycle assessments'.

further enables commodities produced from one particular industry to be distinguished from the same commodity produced by another industry, and to test out the impacts of differing technology and sales structure assumptions on an environmental supply chain analysis results.

B.3 Application

B.3.1 Estimation of Commodity-by-Commodity Tables Using the Bohlin and Widell Model

As a short introduction to the application section, it is interesting to consider the extent to which the models described in this appendix improve on the original Bohlin and Widell method for estimating SIOTs. Recall that a major drawback of the Bohlin and Widell model, unlike the models developed in this appendix, is that it produces tables that do not necessarily balance. In order to illustrate this limitation, two commodity-by-commodity SIOTs have been produced using the Bohlin and Widell model, based on data contained within the latest available SUTs for New Zealand (Statistics New Zealand, 2007). For the first table, full weight is given to the CTA for all commodities (μ_i=5000; ω_i=0), while for the second table the ITA is applied to all commodities (μ_i=0; ω_i=5000). The row and column imbalances in the two tables are measured according to the median of the deviation in row and column totals for each respective commodity, i.e.

$$\text{median}\left(\frac{\left|\alpha_i - \alpha'_{i'}\right|}{0.5\left(\alpha_i - \alpha'_{i'}\right)}\right)\times 100 \text{ , for all } i=i',$$

with α_i defined as the total value of the sales of commodity i to all intermediate and final demands, and $\alpha'_{i'}$ is the total cost of all commodity and primary inputs in the production of commodity i'.

Not surprisingly, the ITA table produced from the Bohlin and Widell model is near to exactly balanced (i.e. the median deviation in row and column totals is 0.0 percent). This is a reflection of the unique solution to the ITA table as already described. When the CTA assumption is applied, however, the median deviation in row and column totals is around 2.0 percent. Although this degree of imbalance in the CTA table is not extreme, it is not quite negligible either. The results do, nevertheless, indicate that for some applications, it is possible that the Bohlin and Widell model will produce a table that is near-enough to being

balanced. The problem is that a practitioner will not know if this will occur for any particular set of data and combination of technology assumptions, without actually carrying out all of the work required to run the Bohlin and Widell model. Added to this is the difficulty of applying the technology assumptions in the Bohlin and Widell model as already discussed in *Extension 3* above.

B.3.2 Comparing Input-Output Tables Produced by the Commodity-by-Commodity, Industry-by-Industry and Comprehensive Models

The focus of the remainder of this section is on exploring the behaviour and outputs produced by the three models that have been developed in this appendix for estimating SIOTs, i.e. the commodity-by-commodity model (Eq. B.6), the industry-by-industry model (Eq. B.12) and the comprehensive model (Eq. B.14).[234] In order to undertake this task we can draw on a sample set of SUTs, derived from the latest available SUTs for New Zealand (Statistics New Zealand, 2007), to produce eight different SIOTs through application of differing technology and sales structure assumptions. The number of different SIOTs that could potentially be produced from the sample SUTs is vast. For simplicity this appendix focuses on the extreme examples, i.e. those SIOTs produced where either all commodities are allocated the ITA or all commodities are allocated the CTA, and either all industries are allocated the FIS assumption or all industries are allocated the FCS assumption. In summary, two tables are produced using the commodity-by-commodity model – one where the ITA is applied to all commodities and one where the CTA is applied to all commodities. Similarly, for the industry-by-industry model, a solely FCS assumption table is produced, as well as a solely FIS assumption table. From the comprehensive model four tables are produced: (1) a CTA, FCS table; (2) a CTA, FIS table; (3) an ITA, FCS table; and (4) an ITA, FIS table.

Each of the SIOTs produced are compared against the other SIOTs in terms of the median percentage deviation in technical coefficients. In equation form, the comparison between two commodity-by-commodity tables is therefore calculated by,

[234] As the focus of this application is on comparing technical coefficients derived for the intermediate demand components of the IO tables, Eqs. B.6, B.12 and B.14 have been used to derive the three models rather than Eqs. B.7,B.13 and B.15. The variables specifying primary demands by receiving industry and output commodity (i.e. the $p_{i'js}$) and final demands by commodity consumed and supplying industry (i.e. the $f_{ij'}$s) are simply estimated exogenously. For each industry, primary inputs are allocated to commodity outputs on a pro rata basis according to the proportion that each commodity makes up of the industry's total supply. Similarly final demands by commodity are allocated to supplying industries according to each industry's share of the total supply of that commodity.

$$\text{median}\left(\frac{\left|a_{ii'}-\overline{a_{ii'}}\right|}{0.5\left(a_{ii'}+\overline{a_{ii'}}\right)}\right)\times 100\,, \qquad \text{(B.16)}$$

where $a_{ii'}$ is, the technical coefficient for inputs of commodity i in the production of commodity i' in the first table,[235] and $\overline{a_{ii'}}$ is the technical coefficient for inputs of the same commodity i in the production of the same commodity i' in the second table. An analogous equation is used for comparing industry-by-industry tables.

Note that the median percentage deviation is just one of a number of different measures that could be used to compare technical coefficients between tables. A primary advantage of this measure, and the reason that it is selected for use in this application, is that it is sensitive to deviations in the smaller technical coefficients, as well as in the larger. One alternative measure is, for example, the sum of the absolute deviations in technical coefficients, divided by the sum of the coefficients, i.e. in percentage terms,

$$\frac{\sum_{ii'} a_{ii'}-\overline{a_{ii'}}}{\sum_{ii'} 0.5\left(a_{ii'}+\overline{a_{ii'}}\right)}\times 100\,.$$

Compared with the measure selected for this appendix, this alternative measure will be more heavily influenced by the extent of the deviations in the larger coefficients, as in absolute terms these deviations will constitute a significant proportion of the total sum of the deviations.

Another alternative measure is to use the mean of the percentage deviation in technical coefficients for Eq. B.16, rather than the median. Of course if there are just a few coefficients that vary quite substantially, the mean measure will be heavily influenced by these outliers, and in these cases the median is likely to provide a better representation of the central tendency of the set of deviations. This is not to say that the mean may not be a valid alternative measure. Large variations in coefficients are important, even if it is not in the

[235] By convention, the symbol 'a' is used to denote a technical (Leontief) coefficient. Such coefficients, however, must not be confused with elements of the matrix $\tilde{\mathbf{A}}$ as specified in Figure 3.4. within Chapter 3.

majority of the coefficients, and the mean can help in identifying these. Both the mean and median percentage deviations in technical coefficients were investigated and as there were not significant differences in the results, only the median results are reported here.

Tables B.3 and B.4 below, which present the results of the SIOT comparisons, also provide notes on the weights that were allocated to the various technology and sales share assumptions in order to derive each table.

Table B.3 The Median Percentage Difference in Technical Coefficients for Commodity-by-Commodity Tables Produced Under Different Assumptions

	Industry Technology Assumption (ITA)	Commodity Technology Assumption (CTA), Fixed Commodity Sales Structure (FCS)	Commodity Technology Assumption (CTA), Fixed Industry Sales Structure (FIS)	Industry Technology Assumption (ITA), Fixed Commodity Sales Structure (FCS)	Industry Technology Assumption (ITA), Fixed Industry Sales Structure (FIS)
Commodity Technology Assumption (CTA)	19	11	8	19	20
Industry Technology Assumption (ITA)		11	17	0	3
Commodity Technology Assumption (CTA), Fixed Commodity Sales Structure (FCS)			11	11	12
Commodity Technology Assumption (CTA), Fixed Industry Sales Structure (FIS)				17	16
Industry Technology Assumption (ITA), Fixed Commodity Sales Structure (FCS)					3

Notes: CTA: $\mu_{i'j}$=5000, $\omega_{i'j}$=0 for all i',j; ITA: $\mu_{i'j}$=0, $\omega_{i'j}$=5000 for all i',j; CTA,FCS: $\mu_{i'j}$=5000, $\omega_{i'j}$=0 for all i',j and $\alpha_{ij'}$=5000, $\beta_{ij'}$=0 for all i,j'; CTA,FIS: $\mu_{i'j}$=5000, $\omega_{i'j}$=0 for all i',j and $\alpha_{ij'}$=0, $\beta_{ij'}$=5000 for all i,j'; ITA, FCS: $\mu_{i'j}$=0, $\omega_{i'j}$=5000 for all i',j and α_{ij}=5000, $\beta_{ij'}$=0 for all i,j'; ITA, FIS: $\mu_{i'j}$=0, $\omega_{i'j}$=5000 for all i',j and $\alpha_{ij'}$=0, $\beta_{ij'}$=5000 for all i,j'.

Table B.4 The Median Percentage Difference in Technical Coefficients for Industry-by-Industry Tables Produced Under Different Assumptions

	Fixed Industry Sales Structure (FIS)	Commodity Technology Assumption (CTA), Fixed Commodity Sales Structure (FCS)	Commodity Technology Assumption (CTA), Fixed Industry Sales Structure (FIS)	Industry Technology Assumption (ITA), Fixed Commodity Sales Structure (FCS)	Industry Technology Assumption (ITA), Fixed Industry Sales Structure (FIS)
Fixed Commodity Sales Structure (FCS)	20	0	19	0	19
Fixed Industry Sales Structure (FIS)		21	5	20	0
Commodity Technology Assumption (CTA), Fixed Commodity Sales Structure (FCS)			19	1	19
Commodity Technology Assumption (CTA), Fixed Industry Sales Structure (FIS)				19	4
Industry Technology Assumption (ITA), Fixed Commodity Sales Structure (FCS)					20

Notes: FCS: $\alpha_{ij'}$=5000, $\beta_{ij'}$=0 for all i,j'; FIS: $\alpha_{ij'}$=0, $\beta_{ij'}$=5000 for all i,j'; CTA,FCS: $\mu_{i'j}$=5000, $\omega_{'j}$=0 for all i',j and $\alpha_{ij'}$=5000, $\beta_{ij'}$=0 for all i,j'; CTA,FIS: $\mu_{i'j}$=5000, $\omega_{i'j}$=0 for all i',j and $\alpha_{ij'}$=0, $\beta_{ij'}$=5000 for all i,j'; ITA, FCS: $\mu_{i'j}$=0, $\omega_{i'j}$=5000 for all i',j and α_{ij}=5000, $\beta_{ij'}$=0 for all i,j'; ITA, FIS: $\mu_{i'j}$=0, $\omega_{i'j}$=5000 for all i',j and $\alpha_{ij'}$=0, $\beta_{ij'}$=5000 for all i,j'.

The most obvious result from this example application is that the technical coefficients are dramatically influenced by the technology/sales structure assumptions applied. For most IO practitioners, this will be an insight of which they are already well aware. It can be noted, for example, that the technical coefficients of the commodity-by-commodity tables vary on average by up to 20 percent in the sample tables derived. Similarly, in the industry-by-industry tables, the range of percentage deviations in the technical coefficients is up to 21 percent.

The most interesting results presented by this application are the comparisons between the tables produced by the commodity-by-commodity model and the industry-by-industry model with those generated from the comprehensive model. In these regards, one of the important observations is that the table produced by the commodity-by-commodity model through application of the ITA assumption is nearly identical to the table produced by the comprehensive model through application of the ITA and FCS assumptions. Similarly, in terms of the industry-by-industry SIOTs, the table generated from just the FCS assumption in the industry-by-industry model is nearly identical to the table generated from the ITA and FCS assumptions in the comprehensive model.

To explain these results, recall that the ITA assumption applied to commodity $i´$ produced by industry j in the comprehensive model means that var($b_{ijj´}$) will be zero for all combinations of i and $j´$. By simply summing across all $j´$ industries it can be concluded where this result is achieved, var (b_{ij}) will also be zero for all of i, which happens to be the ITA solution in the commodity-by-commodity model. Similarly, for the FCS assumption, if var($d_{ii´j}$) equals zero in the comprehensive model, then var(d_{ij}) will also equal zero which is the solution to the industry-by-industry model.

Note, however, that the same results are not achieved when comparisons are made with tables produced under either the CTA or FIS assumptions. The coefficients of the table produced by the commodity-by-commodity model using the FIS assumption, for example, vary on average by 3 percent from the coefficients of the table produced from the comprehensive model using the ITA, FIS assumptions. Essentially, this occurs because it is not possible to find an exact solution to the FIS requirement (because it would involve negative coefficients) and thus the models merely seek to minimize the objective function. In the case of the comprehensive model, the optimal result occurs where the ITA assumption is not quite achieved (i.e. var($b_{ijj´}$) is near to but not equal to zero). However, by not selecting the perfect ITA result, the optimisation model is able to reduce var($d_{i´jj´}$) and thus produce coefficients that

are closer to the FIS assumption. The outcome is therefore that the industry-by-industry table produced by the comprehensive model is impacted by the weights put on the CTA/ITA assumptions.

B.4 Discussion

As a final discussion point it is interesting to consider the number of variables and constraints in the optimisation models that are set out in this appendix. It is these variables that will largely determine the way in which the optimisation models will be implemented in practice, including the selection of appropriate solver engines.

Beginning with the commodity-by-commodity model (Eq. B.6), the number of variables is simply equivalent to the number of b-coefficients. The quantity of b-coefficients can, in turn, be calculated by the number of commodities squared multiplied by the number of industries. Note that although this defines the maximum number of b-coefficients, in practice the number of variables is likely to be significantly less because where a particular type of commodity is not produced by an industry, the relevant b-coefficients will not be included in the model. In equation form the number of variables in the commodity-by-commodity model, v^{com}, is therefore determined as,

$$v^{com} = \bar{\psi}^2\bar{\sigma} - x\bar{\psi},$$

where $\bar{\psi}$ is the number of commodity types, $\bar{\sigma}$ is the number of industry types and x is the number of zero elements in the supply table. Similarly, the number of variables in the industry by industry model (Eq. B.12), v^{ind}, can be calculated as,

$$v^{ind} = \bar{\psi}\bar{\sigma}^2 - x\bar{\sigma}.$$

In the comprehensive model (Eq. B.14), because of the inclusion of an additional dimension, there is quite a substantial increase in the number of variables. The number, v^{ci} can be quantified as,

$$v^{ci} = (\bar{\psi}\bar{\sigma} - x)^2.$$

The implications of sparse matrices are also important to consider when determining the options for implementing the comprehensive model as well as the commodity-by-commodity and industry-by-industry models. In these regards it can be noted that as SUTs become more disaggregate, the proportion of the table that is comprised of zeros increases (because of the less occurrence of joint production). It has, for example, been calculated with respect to New Zealand data that where the supply table is aggregated to dimensions n=10 and m=10, only 5 percent of the matrix is comprised of zeros. When however the dimensions are doubled (i.e. n=20 and m=20), the proportion of zero elements increases to 28 percent. Increasing the dimensions of the SUTs that are used as inputs into the optimisation model will thus not necessarily increase the number of variables by the extent that might initially be anticipated.

By comparison with the number of variables, the number of constraints in all three models is relatively small. For both the commodity-by-commodity and industry-by-industry models the number of constraints is simply the number of elements in the supply table plus the number of elements in the use table, i.e.

$$c^{com} = c^{ind} = 2\bar{\psi}\bar{\sigma},$$

while for the comprehensive model the number of constraints, c^{ci}, is,

$$c^{ci} = 3\bar{\psi}\bar{\sigma}.$$

B.5 Summary

A long-standing issue encountered by IO practitioners has been the need to devise practical methods for producing symmetrical IO tables, based on data contained in SUTs, without the generation of negative coefficients. It is because of the unsatisfactory solutions to this problem that many applications of IO analysis have involved the selection of technology assumptions that would otherwise not be preferred. This appendix has demonstrated that optimisation techniques provide one possible means of overcoming this issue. The two optimisation models presented here for calculating both commodity-by-commodity and industry-by-industry tables provide IO practitioners with the full autonomy to select technology (and sales structure) assumptions as may be appropriate, without the generation

of negative coefficients. An added advantage of these models is the possibility of starting with rectangular supply and use tables as the base data.

The potential drawback of the optimisation approach for producing IO tables is the complexity of the models in terms of the number of optimisation variables involved. It is, however, observed that there are already a number of software options that can be utilised for solving large-scale optimisation problems. The computing resources necessary to solve these problems is also continuously improving.

This appendix has further explored the development of a comprehensive model for the generation of symmetrical IO tables. The advantage of this model is that it can be used to generate both commodity-by-commodity and industry-by-industry tables from the same dataset that are conceptually and mathematically consistent. The major implication of this comprehensive model is that the cells of commodity-by-commodity matrices generated will potentially be impacted by the selection of market share assumptions, and similarly the cells of industry-by-industry matrices generated will potentially be impacted by the selected technology assumptions. These outcomes are quite different from those occurring under other approaches where the technology assumptions only impact on commodity-by-commodity matrices and the market share assumptions only impact on industry-by-industry matrices.

Appendix C

Economic Industry and Commodity Definitions and Concordances

This Appendix provides several concordances. Tables C.1(a) and C.1(b) map the GTAP sectors to the respective CPC and ISIC classification systems. The GTAP classification is unusual in that the primary industries are matched to the CPC, while the manufacturing and service industries concord to the ISIC. Conceptually, each sector may be viewed as both an industry and a commodity, with, for example, the paddy rice sector being the industry responsible for producing rice commodities. Table C.2 maps the United Nations FAO crop commodities to the GTAP sectors. Finally, Table C.3 maps the GTAP sectors to the IO industries used for reporting in Chapter 4, and for the dynamic modelling of Chapter 9.

Table C.1(a) Concordance Mapping Global Trade Analysis Project Sectors to Central Product Classification

	GTAP Code	GTAP Description	Central Product Classification Code
1	pdr	Paddy rice	113-114
2	wht	Wheat	111
3	gro	Other grains	112, 115-116, 119
4	v_f	Vegetables, fruits	12-13
5	osd	Oil seeds	14
6	c_b	Sugar cane	18
7	pfb	Plant-based fibers	192
8	ocr	Other crops	15-17, 191, 193-194, 199
9	ctl	Cattle, sheep	211, 299
10	oap	Animal products	212, 292-295, 297-298
11	rmk	Raw milk	291
12	wol	Wool	296
13	frs	Forestry	3
19	cmt	Cattle, sheep meat	21111-21112, 21115-21119, 2161
20	omt	Other meat	21113-21114, 2112-2114, 2162
21	vol	Vegetable oils	2163-2169, 217-218
22	mil	Dairy products	22
23	pcr	Processed rice	2316
24	sgr	Sugar cane	235
25	ofd	Other food	212-215, 2311-2315, 2317-2318, 232-234, 236-237, 239
26	b_t	Beverages, tobacco	24-25

Table C.1(b) Concordance Mapping Global Trade Analysis Project Sectors to International Standard Industry Classification Revision 3

	GTAP Code	GTAP Description	International Standard Industrial Classification Rev. 3
14	fsh	Fishing	5, 15
15	coa	Coal	101-103
16	oil	Oil	111 (part), 112 (part)
17	gas	Gas	111 (part), 112 (part)
18	omn	Other minerals	12-14
27	tex	Textiles	17, 243
28	wap	Wearing apparel	18
29	lea	Leather products	19
30	lum	Wood products	20
31	ppp	Paper products	21-22
32	p_c	Petroleum	231-233
33	crp	Chemicals, rubber	241-242, 25
34	nmm	Mineral products	26
35	i_s	Ferrous metals	271, 2731
36	nfm	Other metals	272, 2732
37	fmp	Metal products	28
38	mvh	Motor vehicles	34
39	otn	Transport equipment	35
40	ele	Electronic equipt	30, 32
41	ome	Machiner equipt	29, 31, 33
42	omf	Other manufactures	36-37
43	ely	Electricity	401
44	gdt	Gas distribution	402, 403
45	wtr	Water	41
46	cns	Construction	45
47	trd	Trade	50-51, 521-526, 55
48	otp	Other transport	60, 63
49	wtp	Water transport	61
50	atp	Air transport	62
51	cmn	Communication	64
52	ofi	Financial services	65, 67
53	isr	Insurance	66
54	obs	Business services	K
55	ros	Recreatl services	92-93, 95
56	osg	Education, health	75, 80, 85, 90-91, 99
57	dwe	Dwellings	n.a.

Table C.2 Concordance of FAO Crop Commodity to Global Trade Analysis Project Sectors

FAO Crop Commodity	GTAP Code	GTAP Description
Agave Fibres Nes	pfb	Plant-based fibers
Alfalfa for forage and silage	ocr	Other crops
Almonds, with shell	v_f	Vegetables, fruits
Anise, badian, fennel, corian.	ocr	Other crops
Apple juice, concentrated	ofd	Other food
Apple juice, single strength	ofd	Other food
Apples	v_f	Vegetables, fruits
Apricots	v_f	Vegetables, fruits
Arecanuts	v_f	Vegetables, fruits
Artichokes	v_f	Vegetables, fruits
Asparagus	v_f	Vegetables, fruits
Avocados	v_f	Vegetables, fruits
Bambara beans	v_f	Vegetables, fruits
Bananas	v_f	Vegetables, fruits
Barley	gro	Other grains
Beans, dry	v_f	Vegetables, fruits
Beans, green	v_f	Vegetables, fruits
Beets for Fodder	ocr	Other crops
Berries Nes	v_f	Vegetables, fruits
Blueberries	v_f	Vegetables, fruits
Brazil nuts, with shell	v_f	Vegetables, fruits
Broad beans, horse beans, dry	v_f	Vegetables, fruits
Buckwheat	gro	Other grains
Cabbage for Fodder	ocr	Other crops
Cabbages and other brassicas	v_f	Vegetables, fruits
Canary seed	gro	Other grains
Carobs	v_f	Vegetables, fruits
Carrots and turnips	v_f	Vegetables, fruits
Carrots for Fodder	ocr	Other crops
Cashew nuts, with shell	v_f	Vegetables, fruits
Cashewapple	v_f	Vegetables, fruits
Cassava	v_f	Vegetables, fruits
Cassava leaves	v_f	Vegetables, fruits
Castor oil seed	osd	Oil seeds
Cauliflowers and broccoli	v_f	Vegetables, fruits
Cereals, nes	gro	Other grains
Cherries	v_f	Vegetables, fruits
Chestnuts	v_f	Vegetables, fruits
Chick peas	v_f	Vegetables, fruits
Chicory roots	v_f	Vegetables, fruits
Chillies and peppers, dry	v_f	Vegetables, fruits
Chillies and peppers, green	v_f	Vegetables, fruits
Cinnamon (canella)	ocr	Other crops

Table C.2 Concordance of FAO Crop Commodity to Global Trade Analysis Project Sectors (Cont.)

FAO Crop Commodity	GTAP Code	GTAP Description
Citrus fruit, nes	v_f	Vegetables, fruits
Citrus juice, concentrated	ofd	Other food
Citrus juice, single strength	ofd	Other food
Clover for forage and silage	ocr	Other crops
Cloves	ocr	Other crops
Cocoa beans	ocr	Other crops
Coconuts	v_f	Vegetables, fruits
Coffee, green	ocr	Other crops
Coir	pfb	Plant-based fibers
Cotton lint	pfb	Plant-based fibers
Cottonseed	osd	Oil seeds
Cow peas, dry	v_f	Vegetables, fruits
Cranberries	v_f	Vegetables, fruits
Cucumbers and gherkins	v_f	Vegetables, fruits
Currants	v_f	Vegetables, fruits
Dates	v_f	Vegetables, fruits
Dry Apricots	v_f	Vegetables, fruits
Eggplants (aubergines)	v_f	Vegetables, fruits
Fibre Crops Nes	pfb	Plant-based fibers
Figs	v_f	Vegetables, fruits
Figs Dried	v_f	Vegetables, fruits
Flax fibre and tow	pfb	Plant-based fibers
Flour of Fruits	ofd	Other food
Fonio	v_f	Vegetables, fruits
forage Products	ocr	Other crops
Fruit Dried Nes	v_f	Vegetables, fruits
Fruit Fresh Nes	v_f	Vegetables, fruits
Fruit Juice Nes	ofd	Other food
Fruit Prp Nes	v_f	Vegetables, fruits
Fruit Tropical Dried Nes	v_f	Vegetables, fruits
Fruit, tropical fresh nes	v_f	Vegetables, fruits
Fruit,Nut,Peel, Sugar Prs	ofd	Other food
Garlic	v_f	Vegetables, fruits
Ginger	v_f	Vegetables, fruits
Gooseberries	v_f	Vegetables, fruits
Grape Juice	ofd	Other food
Grapefruit (inc. pomelos)	v_f	Vegetables, fruits
Grapefruit juice, concentrated	ofd	Other food
Grapes	v_f	Vegetables, fruits
Grasses Nes for forage;Sil	ocr	Other crops
Green Oilseeds for Silage	ocr	Other crops
Groundnuts, with shell	ofd	Other food
Gums Natural	frs	Forestry

Table C.2 Concordance of FAO Crop Commodity to Global Trade Analysis Project Sectors (Cont.)

FAO Crop Commodity	GTAP Code	GTAP Description
Hazelnuts, with shell	v_f	Vegetables, fruits
Hemp Tow Waste	tex	Textiles
Hempseed	osd	Oil seeds
Homogen. Cooked Fruit Prp	ofd	Other food
Hops	gro	Other grains
Jojoba Seeds	osd	Oil seeds
Juice of Grapefruit	ofd	Other food
Juice of Pineapples	ofd	Other food
Jute	pfb	Plant-based fibers
Kapok Fibre	pfb	Plant-based fibers
Kapokseed in Shell	osd	Oil seeds
Karite Nuts (Sheanuts)	v_f	Vegetables, fruits
Kiwi fruit	v_f	Vegetables, fruits
Kolanuts	v_f	Vegetables, fruits
Leeks, other alliaceous veg	v_f	Vegetables, fruits
Leguminous for Silage	ocr	Other crops
Leguminous vegetables, nes	v_f	Vegetables, fruits
Lemon juice, concentrated	ofd	Other food
Lemon juice, single strength	ofd	Other food
Lemons and limes	v_f	Vegetables, fruits
Lentils	v_f	Vegetables, fruits
Lettuce and chicory	v_f	Vegetables, fruits
Linseed	osd	Oil seeds
Lupins	ocr	Other crops
Maize	gro	Other grains
Maize for forage and silage	ocr	Other crops
Maize, green	gro	Other grains
Mango Juice	ofd	Other food
Mango Pulp	ofd	Other food
Mangoes, mangosteens, guavas	v_f	Vegetables, fruits
Manila Fibre (Abaca)	pfb	Plant-based fibers
Marc of Grapes	v_f	Vegetables, fruits
Maté	pfb	Plant-based fibers
Melonseed	ofd	Other food
Millet	gro	Other grains
Mixed grain	gro	Other grains
Mushrooms and truffles	v_f	Vegetables, fruits
Mustard seed	osd	Oil seeds
Natural rubber	frs	Forestry
Nutmeg, mace and cardamoms	ocr	Other crops
Nuts, nes	v_f	Vegetables, fruits
Oats	gro	Other grains
Oil palm fruit	v_f	Vegetables, fruits

Table C.2 Concordance of FAO Crop Commodity to Global Trade Analysis Project Sectors (Cont.)

FAO Crop Commodity	GTAP Code	GTAP Description
Oilseeds, Nes	osd	Oil seeds
Okra	v_f	Vegetables, fruits
Olives	v_f	Vegetables, fruits
Onions (inc. shallots), green	v_f	Vegetables, fruits
Onions, dry	v_f	Vegetables, fruits
Orange juice, concentrated	ofd	Other food
Orange juice, single strength	ofd	Other food
Oranges	v_f	Vegetables, fruits
Other Bastfibres	pfb	Plant-based fibers
Other melons (inc.cantaloupes)	v_f	Vegetables, fruits
Palm kernels	osd	Oil seeds
Palm oil	vol	Vegetable oils
Papayas	v_f	Vegetables, fruits
Peaches and nectarines	v_f	Vegetables, fruits
Pears	v_f	Vegetables, fruits
Peas, dry	v_f	Vegetables, fruits
Peas, green	v_f	Vegetables, fruits
Pepper (Piper spp.)	v_f	Vegetables, fruits
Peppermint	ocr	Other crops
Persimmons	v_f	Vegetables, fruits
Pigeon peas	v_f	Vegetables, fruits
Pineapple Juice Conc	ofd	Other food
Pineapples	v_f	Vegetables, fruits
Pineapples Cand	v_f	Vegetables, fruits
Pistachios	v_f	Vegetables, fruits
Plantains	v_f	Vegetables, fruits
Plum juice, concentrated	ofd	Other food
Plums and sloes	v_f	Vegetables, fruits
Plums Dried (Prunes)	v_f	Vegetables, fruits
Pome fruit, nes	v_f	Vegetables, fruits
Popcorn	ocr	Other crops
Poppy seed	osd	Oil seeds
Potatoes	v_f	Vegetables, fruits
Pulses, nes	v_f	Vegetables, fruits
Pumpkins for Fodder	ocr	Other crops
Pumpkins, squash and gourds	v_f	Vegetables, fruits
Pyrethrum,Dried	ocr	Other crops
Quinces	v_f	Vegetables, fruits
Quinoa	ocr	Other crops
Raisins	v_f	Vegetables, fruits
Ramie	pfb	Plant-based fibers
Rapeseed	osd	Oil seeds
Raspberries	v_f	Vegetables, fruits

Table C.2 Concordance of FAO Crop Commodity to Global Trade Analysis Project Sectors (Cont.)

FAO Crop Commodity	GTAP Code	GTAP Description
Rice, paddy	pdr	Paddy rice
Roots and Tubers, nes	v_f	Vegetables, fruits
Rye	gro	Other grains
Rye grass for forage & silage	ocr	Other crops
Safflower seed	osd	Oil seeds
Seed cotton	osd	Oil seeds
Sesame seed	osd	Oil seeds
Sisal	pfb	Plant-based fibers
Sorghum	gro	Other grains
Sorghum for forage and silage	ocr	Other crops
Sour cherries	v_f	Vegetables, fruits
Soybeans	osd	Oil seeds
Spices, nes	ocr	Other crops
Spinach	v_f	Vegetables, fruits
Stone fruit, nes	v_f	Vegetables, fruits
Strawberries	v_f	Vegetables, fruits
String beans	v_f	Vegetables, fruits
Sugar beet	c_b	Sugar cane
Sugar cane	c_b	Sugar cane
Sugar crops, nes	c_b	Sugar cane
Sunflower seed	osd	Oil seeds
Swedes for Fodder	ocr	Other crops
Sweet potatoes	v_f	Vegetables, fruits
Tangerine Juice	ofd	Other food
Tangerines, mandarins, clem.	v_f	Vegetables, fruits
Taro (cocoyam)	v_f	Vegetables, fruits
Tea	ocr	Other crops
Tea Nes	ocr	Other crops
Tobacco, unmanufactured	ocr	Other crops
Tomatoes	v_f	Vegetables, fruits
Triticale	gro	Other grains
Tung Nuts	v_f	Vegetables, fruits
Turnips for Fodder	ocr	Other crops
Vanilla	ocr	Other crops
Vegetables fresh nes	v_f	Vegetables, fruits
Vegetables Roots Fodder	ocr	Other crops
Vetches	ocr	Other crops
Walnuts, with shell	v_f	Vegetables, fruits
Watermelons	v_f	Vegetables, fruits
Wheat	wht	Wheat
Yams	v_f	Vegetables, fruits
Yautia (cocoyam)	v_f	Vegetables, fruits

Table C.3 Concordance Mapping Global Trade Analysis Project Sectors to Input-Output Sectors

	GTAP Code	GTAP Description	Input-Output Code	Input-Output Name
1	pdr	Paddy rice	1	Crops
2	wht	Wheat	1	Crops
3	gro	Other grains	1	Crops
4	v_f	Vegetables, fruits	1	Crops
5	osd	Oil seeds	1	Crops
6	c_b	Sugar cane	1	Crops
7	pfb	Plant-based fibers	1	Crops
8	ocr	Other crops	1	Crops
9	ctl	Cattle, sheep	2	Animals and unprocessed animal products
10	oap	Animal products	2	Animals and unprocessed animal products
11	rmk	Raw milk	2	Animals and unprocessed animal products
12	wol	Wool	2	Animals and unprocessed animal products
13	frs	Forestry	3	Forestry
14	fsh	Fishing	2	Animals and unprocessed animal products
15	coa	Coal	4	Coal
16	oil	Oil	5	Oil
17	gas	Gas	6	Gas and gas distribution
18	omn	Other minerals	10	Chemical and mineral manufacturing
19	cmt	Cattle, sheep meat	7	Food and fibre products
20	omt	Other meat	7	Food and fibre products
21	vol	Vegetable oils	7	Food and fibre products
22	mil	Dairy products	7	Food and fibre products
23	pcr	Processed rice	7	Food and fibre products
24	sgr	Sugar cane	7	Food and fibre products
25	ofd	Other food	7	Food and fibre products
26	b_t	Beverages, tobacco	7	Food and fibre products
27	tex	Textiles	7	Food and fibre products
28	wap	Wearing apparel	7	Food and fibre products
29	lea	Leather products	7	Food and fibre products
30	lum	Wood products	8	Wood and paper products
31	ppp	Paper products	8	Wood and paper products
32	p_c	Petroleum	9	Petroleum manufacturing
33	crp	Chemicals, rubber	10	Chemical and mineral manufacturing
34	nmm	Mineral products	10	Chemical and mineral manufacturing
35	i_s	Ferrous metals	11	Other manufacturing
36	nfm	Other metals	11	Other manufacturing
37	fmp	Metal products	11	Other manufacturing
38	mvh	Motor vehicles	11	Other manufacturing
39	otn	Transport equipment	11	Other manufacturing
40	ele	Electronic equipt	11	Other manufacturing
41	ome	Machiner equipt	11	Other manufacturing
42	omf	Other manufactures	11	Other manufacturing
43	ely	Electricity	12	Electricity
44	gdt	Gas distribution	6	Gas and gas distribution
45	wtr	Water	13	Water
46	cns	Construction	14	Construction
47	trd	Trade	16	Services
48	otp	Other transport	15	Transport
49	wtp	Water transport	15	Transport
50	atp	Air transport	15	Transport
51	cmn	Communication	16	Services
52	ofi	Financial services	16	Services
53	isr	Insurance	16	Services
54	obs	Business services	16	Services
55	ros	Recreatl services	16	Services
56	osg	Education, health	16	Services
57	dwe	Dwellings	16	Services
100	fd	Households	17	Households

Appendix D

Within Environment Flows

To conserve space, this Appendix combines the within-environment accounts into a single matrix, for each element cycle (Table D.1 for C, D.2 for N, D.3 for P, and D.4 for S), defined as, $\tilde{\mathbf{B}} - \left(\tilde{\mathbf{A}}\right)^{\mathrm{T}}$. Positive entries within the matrix indicate the supply of an environmental commodity by an environmental process ($\tilde{\mathbf{B}}$), while negative entries indicate the use of an environmental commodity by an environmental process ($\tilde{\mathbf{A}}$). Net accumulations in environmental commodity stocks ($\tilde{\mathbf{q}}$) are obtained by summing the columns of this matrix, but also requires accounting for inputs to, and outputs from, the economy. Finally, Table D.5 provides a concordance mapping the within environment biogeochemical flows between different definitions sets are applied in Chapters 5, 6 and 8.

Table D.1 Carbon Cycle Flows

		1	2	3	4	5	6
		C dioxide	Methane	C monoxide	Volatile organic C	Carbonyl sulfide	C disulfide
		CO_2	CH_4	CO	C_xH_x	COS	CS_2
		Pg C	Pg C	Pg C	Pg C	Pg C	Pg C
C8	Atmos. destruction of CS_2					6.49E-05	-6.49E-05
C9	Atmos. destruction of DMS	1.94E-02				3.40E-05	
C11	Atmos. destruction of OCS	3.60E-05				-3.60E-05	
C12	$CaCO_3$ deposition in deep sediments						
C13	$CaCO_3$ dissolution in deep ocean						
C14	$CaCO_3$ dissolution in deep sediments						
C15	$CaCO_3$ dissolution in surface ocean						
C16	$CaCO_3$ production by consumers						
C17	$CaCO_3$ production by producers						
C18	CH_4 emissions from natural wetlands		1.34E-01				
C19	Coal loss						
C20	Deep burial of inorganic sediments						
C21	Deep burial of organic sediments						
C22	Denitrification deep ocean						
C23	Denitrification sediments						
C24	Denitrification surface ocean						
C25	Deposition of organics in coastal sediments						
C26	Deposition of organics in deep sediments						
C27	Emissions from solid waste disposal sites	8.08E-02	2.76E-02				
C29	Export of $CaCO_3$ to deep ocean						
C30	Export of inorganics to the oceans						
C31	Export of organics to deep ocean						
C32	Export of soil organics to the oceans						
C33	Extracelluar release of organics						
C34	Geological emissions of CH_4		8.98E-03				
C35	Geological emissions of CO_2	4.76E-02					
C36	Geological emissions of S gases					5.99E-05	7.89E-06
C37	Geological transformation of kerogen						
C38	Hydrothermal inputs of $CaCO_3$						
C41	Litter decomposition						
C42	Marine consumer production						
C43	Mortality of marine consumers						
C44	Mortality of marine producers						
C45	Mortality of zoomas						
C47	Natural gas loss		5.88E-07				
C48	Net $CaCO_3$ deposition in coastal sediments						
C50	Ocean NPP						
C53	Other deep ocean detrital processing						
C54	Other emissions from natural wetlands					4.65E-06	2.44E-06
C55	Other sediments organic processing						
C56	Other soil processing	4.73E+01	-2.41E-02	-2.31E-01		-1.47E-04	-4.21E-05
C57	Other surface ocean detrital processing		9.36E-03	2.14E-02		7.30E-05	3.46E-05
C58	Other zoomass processes	4.27E+00	2.77E-02				
C59	Oxidation of CH_4		-4.43E-01	4.43E-01			
C60	Oxidation of CO	1.09E+00		-1.09E+00			
C62	Oxidation of VOCs to CO			1.84E-01	-1.84E-01		
C63	Oxidation of VOCs to CO_2	4.28E-01			-4.28E-01		
C64	Petroleum loss						
C65	Release of CH_4 from hydrates		3.49E-03				
C66	Release of CO_2 from the oceans	9.06E+01					
C71	Sedimentation of organic soils						
C72	Soil denitrification	1.42E-01					
C74	Subduction						
C76	Terrestrial NPP (excl. crops)	-5.42E+01		5.87E-02	3.30E-01	-9.03E-05	
C77	Uptake of CO_2 by the oceans	-9.28E+01					
C78	Vegetation litterfall						
C79	Weathering of crustal rocks	-2.00E-01					
C80	Wildfires	4.04E-01	2.62E-03	3.20E-02	3.93E-03	1.23E-06	
	Anthrosphere	7.04E+00	2.54E-01	5.82E-01	2.78E-01	3.52E-05	6.20E-05
	Net stock change	4.10E+00	7.49E-04	-4.01E-03		-9.10E-07	

Table D.1 Carbon Cycle Flows (Cont.)

		7	8	9	10	11	12
		Dimethyl sulfide	Vegetation C	Zoomas C	Litter/ detritus C	Other soil organic matter C	Soil inorganic C
		$(CH_3)_2S$	$C_{790}N_{7.6}S3.1P_1$	$C_{115.8}N_{14.5}S_{0.2}P_1$	C	C	CO_3^{2-}
		Pg C	Pg C	Pg C	Pg C	Pg C	Pg C
C8	Atmos. destruction of CS_2						
C9	Atmos. destruction of DMS	-1.94E-02					
C11	Atmos. destruction of OCS						
C12	$CaCO_3$ deposition in deep sediments						
C13	$CaCO_3$ dissolution in deep ocean						
C14	$CaCO_3$ dissolution in deep sediments						
C15	$CaCO_3$ dissolution in surface ocean						
C16	$CaCO_3$ production by consumers						
C17	$CaCO_3$ production by producers						
C18	CH_4 emissions from natural wetlands					-1.34E-01	
C19	Coal loss					4.93E-06	
C20	Deep burial of inorganic sediments						
C21	Deep burial of organic sediments						
C22	Denitrification deep ocean						
C23	Denitrification sediments						
C24	Denitrification surface ocean						
C25	Deposition of organics in coastal sediments						
C26	Deposition of organics in deep sediments						
C27	Emissions from solid waste disposal sites						
C29	Export of $CaCO_3$ to deep ocean						
C30	Export of inorganics to the oceans						-4.50E-01
C31	Export of organics to deep ocean						
C32	Export of soil organics to the oceans					-3.77E-01	
C33	Extracelluar release of organics	1.80E-02					
C34	Geological emissions of CH_4						
C35	Geological emissions of CO_2						
C36	Geological emissions of S gases						
C37	Geological transformation of kerogen						
C38	Hydrothermal inputs of $CaCO_3$						
C41	Litter decomposition				-4.81E+01	4.81E+01	
C42	Marine consumer production						
C43	Mortality of marine consumers						
C44	Mortality of marine producers						
C45	Mortality of zoomas			-4.00E-01	4.00E-01		
C47	Natural gas loss						
C48	Net $CaCO_3$ deposition in coastal sediments						
C50	Ocean NPP						
C53	Other deep ocean detrital processing						
C54	Other emissions from natural wetlands	3.59E-05				-4.30E-05	
C55	Other sediments organic processing						
C56	Other soil processing	1.12E-04				-4.70E+01	5.00E-02
C57	Other surface ocean detrital processing						
C58	Other zoomass processes		-4.70E+00	4.00E-01			
C59	Oxidation of CH_4						
C60	Oxidation of CO						
C62	Oxidation of VOCs to CO						
C63	Oxidation of VOCs to CO_2						
C64	Petroleum loss					1.07E-06	
C65	Release of CH_4 from hydrates						
C66	Release of CO_2 from the oceans						
C71	Sedimentation of organic soils					-4.93E-06	
C72	Soil denitrification					-1.42E-01	
C74	Subduction						
C76	Terrestrial NPP (excl. crops)	1.12E-03	5.39E+01				
C77	Uptake of CO_2 by the oceans						
C78	Vegetation litterfall		-4.36E+01		4.36E+01		
C79	Weathering of crustal rocks						4.00E-01
C80	Wildfires		-4.13E-01		4.13E-02	-8.25E-02	
	Anthrosphere	1.75E-04	-4.50E+00		4.06E+00	-2.54E-01	
	Net stock change		6.00E-01			1.10E-01	

Table D.1 Carbon Cycle Flows (Cont.)

		13	14	15	16	17	18
		Landfilled solid waste C	Kerogen C	Coal C	Petroleum C	Natural gas C	Carbonate minerals
		C	C	$C_{131}N_2S_1P_{0.2}$	$C_{129}N_1S_1$	$C_nH_{(2n+2)}$	CO_3^-
		Pg C	Pg C	Pg C	Pg C	Pg C	Pg C
C8	Atmos. destruction of CS_2						
C9	Atmos. destruction of DMS						
C11	Atmos. destruction of OCS						
C12	$CaCO_3$ deposition in deep sediments						
C13	$CaCO_3$ dissolution in deep ocean						
C14	$CaCO_3$ dissolution in deep sediments						
C15	$CaCO_3$ dissolution in surface ocean						
C16	$CaCO_3$ production by consumers						
C17	$CaCO_3$ production by producers						
C18	CH_4 emissions from natural wetlands						
C19	Coal loss			-6.63E-06			
C20	Deep burial of inorganic sediments						2.80E-01
C21	Deep burial of organic sediments		1.79E-01				
C22	Denitrification deep ocean						
C23	Denitrification sediments						
C24	Denitrification surface ocean						
C25	Deposition of organics in coastal sediments						
C26	Deposition of organics in deep sediments						
C27	Emissions from solid waste disposal sites	-1.08E-01					
C29	Export of $CaCO_3$ to deep ocean						
C30	Export of inorganics to the oceans						
C31	Export of organics to deep ocean						
C32	Export of soil organics to the oceans						
C33	Extracelluar release of organics						
C34	Geological emissions of CH_4		-8.64E-03				
C35	Geological emissions of CO_2		-6.88E-04				-1.13E-02
C36	Geological emissions of S gases						
C37	Geological transformation of kerogen		-6.59E-06	4.93E-06	1.07E-06	5.88E-07	
C38	Hydrothermal inputs of $CaCO_3$						-4.00E-02
C41	Litter decomposition						
C42	Marine consumer production						
C43	Mortality of marine consumers						
C44	Mortality of marine producers						
C45	Mortality of zoomas						
C47	Natural gas loss					-5.88E-07	
C48	Net $CaCO_3$ deposition in coastal sediments						
C50	Ocean NPP						
C53	Other deep ocean detrital processing						
C54	Other emissions from natural wetlands						
C55	Other sediments organic processing						
C56	Other soil processing						
C57	Other surface ocean detrital processing						
C58	Other zoomass processes						
C59	Oxidation of CH_4						
C60	Oxidation of CO						
C62	Oxidation of VOCs to CO						
C63	Oxidation of VOCs to CO_2						
C64	Petroleum loss				-1.41E-06		
C65	Release of CH_4 from hydrates		-3.49E-03				
C66	Release of CO_2 from the oceans						
C71	Sedimentation of organic soils		4.93E-06				
C72	Soil denitrification						
C74	Subduction		-5.78E-03				-3.02E-02
C76	Terrestrial NPP (excl. crops)						
C77	Uptake of CO_2 by the oceans						
C78	Vegetation litterfall						
C79	Weathering of crustal rocks						-2.00E-01
C80	Wildfires						
	Anthrosphere	3.56E-01		-3.16E+00	-3.10E+00	-2.15E+00	-3.14E-01
	Net stock change	2.48E-01	1.60E-01	-3.16E+00	-3.10E+00	-2.15E+00	-3.15E-01

Table D.1 Carbon Cycle Flows (Cont.)

		19	20	21	22	23	24
		Other lithosphere C	Other ocean inorganic C	Marine photoautotrophs C	Marine consumers C	Surface ocean dcmpsrs & organic C	Surface ocean $CaCO_3$
		C	HCO_3^-	$C_{108}N_{15.5}S_{1.3}P_1$	$C_{103}N_{16.5}S_{1.3}P_1$	C	$CaCO_3$
		Pg C	Pg C	Pg C	Pg C	Pg C	Pg C
C8	Atmos. destruction of CS_2						
C9	Atmos. destruction of DMS						
C11	Atmos. destruction of OCS						
C12	$CaCO_3$ deposition in deep sediments						
C13	$CaCO_3$ dissolution in deep ocean		2.00E-01				
C14	$CaCO_3$ dissolution in deep sediments		3.70E-01				
C15	$CaCO_3$ dissolution in surface ocean		4.40E-01				-4.40E-01
C16	$CaCO_3$ production by consumers		-5.49E-01				5.49E-01
C17	$CaCO_3$ production by producers		-5.01E-01				5.01E-01
C18	CH_4 emissions from natural wetlands						
C19	Coal loss	1.71E-06					
C20	Deep burial of inorganic sediments						
C21	Deep burial of organic sediments						
C22	Denitrification deep ocean		2.19E-03				
C23	Denitrification sediments		1.42E-01				
C24	Denitrification surface ocean		4.94E-02			-4.94E-02	
C25	Deposition of organics in coastal sediments					-1.59E+00	
C26	Deposition of organics in deep sediments						
C27	Emissions from solid waste disposal sites						
C29	Export of $CaCO_3$ to deep ocean						-6.60E-01
C30	Export of inorganics to the oceans		2.50E-01				2.00E-01
C31	Export of organics to deep ocean					-8.18E-01	
C32	Export of soil organics to the oceans					3.77E-01	
C33	Extracelluar release of organics			-9.58E+00		9.56E+00	
C34	Geological emissions of CH_4	-3.40E-04					
C35	Geological emissions of CO_2	-3.56E-02					
C36	Geological emissions of S gases	-6.78E-05					
C37	Geological transformation of kerogen						
C38	Hydrothermal inputs of $CaCO_3$						
C41	Litter decomposition						
C42	Marine consumer production		3.51E+01	-1.48E+01	3.29E+01	-5.31E+01	
C43	Mortality of marine consumers				-3.28E+01	3.28E+01	
C44	Mortality of marine producers			-2.56E+01		2.56E+01	
C45	Mortality of zoomas						
C47	Natural gas loss						
C48	Net $CaCO_3$ deposition in coastal sediments						-1.50E-01
C50	Ocean NPP		-5.00E+01	5.00E+01			
C53	Other deep ocean detrital processing		5.71E-01				
C54	Other emissions from natural wetlands						
C55	Other sediments organic processing		1.51E+00				
C56	Other soil processing						
C57	Other surface ocean detrital processing		1.28E+01			-1.28E+01	
C58	Other zoomass processes						
C59	Oxidation of CH_4						
C60	Oxidation of CO						
C62	Oxidation of VOCs to CO						
C63	Oxidation of VOCs to CO_2						
C64	Petroleum loss	3.42E-07					
C65	Release of CH_4 from hydrates						
C66	Release of CO_2 from the oceans		-9.06E+01				
C71	Sedimentation of organic soils						
C72	Soil denitrification						
C74	Subduction	3.60E-02					
C76	Terrestrial NPP (excl. crops)						
C77	Uptake of CO_2 by the oceans		9.28E+01				
C78	Vegetation litterfall						
C79	Weathering of crustal rocks						
C80	Wildfires	1.15E-02					
	Anthrosphere	3.85E-02			-1.06E-02		
	Net stock change	5.00E-02	2.58E+00				

Table D.1 Carbon Cycle Flows (Cont.)

		25 Deep ocean dcmpsrs & other organic C	26 Deep ocean calcium carbonates	27 Marine sediments organic C	28 Marine sediments $CaCO^3$	29 Anthrosphere C
		C	$CaCO_3$	C	$CaCO_3$	C
		Pg C	Pg C	Pg C	Pg C	Pg C
C8	Atmos. destruction of CS_2					
C9	Atmos. destruction of DMS					
C11	Atmos. destruction of OCS					
C12	$CaCO_3$ deposition in deep sediments		-5.00E-01		5.00E-01	
C13	$CaCO_3$ dissolution in deep ocean		-2.00E-01			
C14	$CaCO_3$ dissolution in deep sediments				-3.70E-01	
C15	$CaCO_3$ dissolution in surface ocean					
C16	$CaCO_3$ production by consumers					
C17	$CaCO_3$ production by producers					
C18	CH_4 emissions from natural wetlands					
C19	Coal loss					
C20	Deep burial of inorganic sediments				-2.80E-01	
C21	Deep burial of organic sediments			-1.79E-01		
C22	Denitrification deep ocean	-2.19E-03				
C23	Denitrification sediments			-1.42E-01		
C24	Denitrification surface ocean					
C25	Deposition of organics in coastal sediments			1.59E+00		
C26	Deposition of organics in deep sediments	-2.44E-01		2.44E-01		
C27	Emissions from solid waste disposal sites					
C29	Export of $CaCO_3$ to deep ocean		6.60E-01			
C30	Export of inorganics to the oceans					
C31	Export of organics to deep ocean	8.18E-01				
C32	Export of soil organics to the oceans					
C33	Extracelluar release of organics					
C34	Geological emissions of CH_4					
C35	Geological emissions of CO_2					
C36	Geological emissions of S gases					
C37	Geological transformation of kerogen					
C38	Hydrothermal inputs of $CaCO_3$		4.00E-02			
C41	Litter decomposition					
C42	Marine consumer production					
C43	Mortality of marine consumers					
C44	Mortality of marine producers					
C45	Mortality of zoomas					
C47	Natural gas loss					
C48	Net $CaCO_3$ deposition in coastal sediments				1.50E-01	
C50	Ocean NPP					
C53	Other deep ocean detrital processing	-5.71E-01				
C54	Other emissions from natural wetlands					
C55	Other sediments organic processing			-1.51E+00		
C56	Other soil processing					
C57	Other surface ocean detrital processing					
C58	Other zoomass processes					
C59	Oxidation of CH_4					
C60	Oxidation of CO					
C62	Oxidation of VOCs to CO					
C63	Oxidation of VOCs to CO_2					
C64	Petroleum loss					
C65	Release of CH_4 from hydrates					
C66	Release of CO_2 from the oceans					
C71	Sedimentation of organic soils					
C72	Soil denitrification					
C74	Subduction					
C76	Terrestrial NPP (excl. crops)					
C77	Uptake of CO_2 by the oceans					
C78	Vegetation litterfall					
C79	Weathering of crustal rocks					
C80	Wildfires					
	Anthrosphere					8.74E-01
	Net stock change					8.74E-01

Table D.2 Nitrogen Cycle Flows

		1	2	3	4	5	6
		Dinitrogen	N Oxides	Nitrous oxide	Ammonia/ Ammonium	Vegetation N	Zoomas N
		N_2	NO_x	N_2O	NH_3/NH_4^+	$C_{790}N_{7.6}S_{3.1}P_1$	$C_{115.8}N_{14.5}S_{0.2}P_1$
		Pg N	Pg N	Pg N	Pg N	Pg N	Pg N
N3	Atmos. deposition of NH_3				-6.45E-02		
N4	Atmos. deposition of NO_3^-		-5.18E-02				
N19	Coal loss						
N20	Deep burial of inorganic sediments						
N21	Deep burial of organic sediments						
N22	Denitrification deep ocean	2.79E-03		1.83E-04			
N23	Denitrification sediments	1.80E-01					
N24	Denitrification surface ocean	5.82E-02		3.82E-03			
N25	Deposition of organics in coastal sediments						
N26	Deposition of organics in deep sediments						
N30	Export of inorganics to the oceans						
N31	Export of organics to deep ocean						
N32	Export of soil organics to the oceans						
N33	Extracelluar release of organics						
N37	Geological transformation of kerogen						
N41	Litter decomposition						
N42	Marine consumer production						
N43	Mortality of marine consumers						
N44	Mortality of marine producers						
N45	Mortality of zoomas						-5.83E-02
N46	N_2 fixation by lightning	-5.40E-03	5.40E-03				
N49	NH_3-hydroxyl reaction		3.00E-04	6.00E-04	-9.00E-04		
N50	Ocean NPP	-1.40E-01					
N53	Other deep ocean detrital processing						
N55	Other sediments organic processing						
N56	Other soil processing			5.54E-03	2.36E-03		
N57	Other surface ocean detrital processing						
N58	Other zoomass processes				1.20E-04	-6.11E-02	5.83E-02
N64	Petroleum loss						
N67	Release of NO_3^- from sediments						
N68	Release of NO_x from soils		8.89E-03				
N71	Sedimentation of organic soils						
N72	Soil denitrification	1.25E-01		5.68E-03			
N73	Stratospheric destruction of N_2O	1.13E-02	2.83E-03	-1.42E-02			
N74	Subduction						
N75	Terrestrial N_2 fixation (excl. agriculture)	-9.30E-02					
N76	Terrestrial NPP (excl. crops)					6.04E-01	
N78	Vegetation litterfall					-4.90E-01	
N79	Weathering of crustal rocks						
N80	Wildfires	1.43E-03	1.37E-03	6.37E-05	7.60E-04	-4.63E-03	
	Anthrosphere	-1.69E-01	3.30E-02	2.09E-03	6.22E-02	-4.21E-02	
	Net stock change	-2.83E-02		3.80E-03		6.73E-03	

Table D.2 Nitrogen Cycle Flows (Cont.)

		7	8	9	10	11	12
		Litter/detritus N	Other soil organic matter N	Soil inorganic N	Landfilled solid waste N	Kerogen N	Coal N
		N	N	NO_3^-/NH_4+	N	N	$C_{131}N_2S_1P_{0.2}$
		Pg N	Pg N	Pg N	Pg N	Pg N	Pg N
N3	Atmos. deposition of NH_3			4.52E-02			
N4	Atmos. deposition of NO_3^-			2.12E-02			
N19	Coal loss		8.46E-08				-1.14E-07
N20	Deep burial of inorganic sediments						
N21	Deep burial of organic sediments					1.49E-02	
N22	Denitrification deep ocean						
N23	Denitrification sediments						
N24	Denitrification surface ocean						
N25	Deposition of organics in coastal sediments						
N26	Deposition of organics in deep sediments						
N30	Export of inorganics to the oceans			-2.14E-02			
N31	Export of organics to deep ocean						
N32	Export of soil organics to the oceans		-4.01E-02				
N33	Extracelluar release of organics						
N37	Geological transformation of kerogen					-8.89E-08	8.46E-08
N41	Litter decomposition	-5.35E-01	5.35E-01				
N42	Marine consumer production						
N43	Mortality of marine consumers						
N44	Mortality of marine producers						
N45	Mortality of zoomas	5.83E-02					
N46	N_2 fixation by lightning						
N49	NH_3-hydroxyl reaction						
N50	Ocean NPP						
N53	Other deep ocean detrital processing						
N55	Other sediments organic processing						
N56	Other soil processing		-6.55E-01	6.47E-01			
N57	Other surface ocean detrital processing						
N58	Other zoomass processes	2.69E-03					
N64	Petroleum loss		4.25E-09				
N67	Release of NO_3^- from sediments						
N68	Release of NO_x from soils			-8.89E-03			
N71	Sedimentation of organic soils		-7.78E-08			7.78E-08	
N72	Soil denitrification		-6.60E-03	-1.24E-01			
N73	Stratospheric destruction of N_2O						
N74	Subduction					-9.13E-05	
N75	Terrestrial N_2 fixation (excl. agriculture)		9.30E-02				
N76	Terrestrial NPP (excl. crops)	-1.51E-01		-4.53E-01			
N78	Vegetation litterfall	4.90E-01					
N79	Weathering of crustal rocks			5.00E-03			
N80	Wildfires	2.83E-03	-1.83E-03				
	Anthrosphere	1.33E-01	7.50E-02	-4.22E-02	1.28E-02		-5.43E-02
	Net stock change			6.90E-02	1.28E-02	1.48E-02	-5.43E-02

Table D.2 Nitrogen Cycle Flows (Cont.)

		13 Petroleum N	14 Other lithosphere N	15 Ocean inorganic N	16 Marine photoautotrophs N	17 Marine consumers N	18 Surface ocean dcmpsrs & organic N
		$C_{129}N_1S_1$	N	NO_3^-/NH_4+	$C_{108}N_{15.5}S_{1.3}P_1$	$C_{103}N_{16.5}S_{1.3}P_1$	N
		Pg N	Pg N	Pg N	Pg N	Pg N	Pg N
N3	Atmos. deposition of NH_3			1.94E-02			
N4	Atmos. deposition of NO_3^-			3.06E-02			
N19	Coal loss		2.93E-08				
N20	Deep burial of inorganic sediments		1.01E-02				
N21	Deep burial of organic sediments						
N22	Denitrification deep ocean			-2.62E-03			
N23	Denitrification sediments						
N24	Denitrification surface ocean			-5.38E-02			-8.27E-03
N25	Deposition of organics in coastal sediments						-2.80E-01
N26	Deposition of organics in deep sediments						
N30	Export of inorganics to the oceans			2.14E-02			
N31	Export of organics to deep ocean						-1.30E-01
N32	Export of soil organics to the oceans						4.01E-02
N33	Extracelluar release of organics				-1.60E+00		1.60E+00
N37	Geological transformation of kerogen	4.25E-09					
N41	Litter decomposition						
N42	Marine consumer production			5.70E+00	-2.48E+00	6.14E+00	-9.35E+00
N43	Mortality of marine consumers					-6.13E+00	6.13E+00
N44	Mortality of marine producers				-4.28E+00		4.28E+00
N45	Mortality of zoomas						
N46	N_2 fixation by lightning						
N49	NH_3-hydroxyl reaction						
N50	Ocean NPP			-8.23E+00	8.37E+00		
N53	Other deep ocean detrital processing			1.10E-01			
N55	Other sediments organic processing						
N56	Other soil processing						
N57	Other surface ocean detrital processing			2.29E+00			-2.29E+00
N58	Other zoomass processes						
N64	Petroleum loss	-3.46E-07	3.42E-07				
N67	Release of NO_3^- from sediments			9.54E-02			
N68	Release of NO_x from soils						
N71	Sedimentation of organic soils						
N72	Soil denitrification						
N73	Stratospheric destruction of N_2O						
N74	Subduction		9.13E-05				
N75	Terrestrial N_2 fixation (excl. agriculture)						
N76	Terrestrial NPP (excl. crops)						
N78	Vegetation litterfall						
N79	Weathering of crustal rocks		-5.00E-03				
N80	Wildfires						
	Anthrosphere	-1.23E-02				-1.98E-03	
	Net stock change	-1.23E-02	5.22E-03	-2.05E-02			

Table D.2 Nitrogen Cycle Flows (Cont.)

		19 Deep ocean dcmpsrs & other organic N	20 Marine sediments organic N	21 Marine sediments ammonium	22 Anthrosphere N
		N	N	NH_4^+	N
		Pg N	Pg N	Pg N	Pg N
N3	Atmos. deposition of NH_3				
N4	Atmos. deposition of NO_3^-				
N19	Coal loss				
N20	Deep burial of inorganic sediments			-1.01E-02	
N21	Deep burial of organic sediments		-1.49E-02		
N22	Denitrification deep ocean	-3.49E-04			
N23	Denitrification sediments		-2.36E-02	-1.56E-01	
N24	Denitrification surface ocean				
N25	Deposition of organics in coastal sediments		2.80E-01		
N26	Deposition of organics in deep sediments	-2.04E-02	2.04E-02		
N30	Export of inorganics to the oceans				
N31	Export of organics to deep ocean	1.30E-01			
N32	Export of soil organics to the oceans				
N33	Extracelluar release of organics				
N37	Geological transformation of kerogen				
N41	Litter decomposition				
N42	Marine consumer production				
N43	Mortality of marine consumers				
N44	Mortality of marine producers				
N45	Mortality of zoomas				
N46	N_2 fixation by lightning				
N49	NH_3-hydroxyl reaction				
N50	Ocean NPP				
N53	Other deep ocean detrital processing	-1.10E-01			
N55	Other sediments organic processing		-2.62E-01	2.62E-01	
N56	Other soil processing				
N57	Other surface ocean detrital processing				
N58	Other zoomass processes				
N64	Petroleum loss				
N67	Release of NO_3^- from sediments			-9.54E-02	
N68	Release of NO_x from soils				
N71	Sedimentation of organic soils				
N72	Soil denitrification				
N73	Stratospheric destruction of N_2O				
N74	Subduction				
N75	Terrestrial N_2 fixation (excl. agriculture)				
N76	Terrestrial NPP (excl. crops)				
N78	Vegetation litterfall				
N79	Weathering of crustal rocks				
N80	Wildfires				
	Anthrosphere				3.03E-03
	Net stock change				3.03E-03

Table D.3 Phosphorus Cycle Flows

		1	2	3	4	5	6
		Phosphate aerosols	Vegetation P	Zoomas P	Litter/detritus P	Other soil organic matter P	Soil inorganic P
		PO_4^{3-}	$C_{790}N_{7.6}S_{3.1}P_1$	$C_{115.8}N_{14.5}S_{0.2}P_1$	P	P	PO_4^{3-}
		Pg P	Pg P	Pg P	Pg P	Pg P	Pg P
P1	Aeolian emissions of PO_4^{3-} aerosols	4.34E-03					-4.34E-03
P5	Atmos. deposition of PO_4^{3-} aerosols	-4.65E-03					3.56E-03
P19	Coal loss					1.96E-08	
P20	Deep burial of inorganic sediments						
P21	Deep burial of organic sediments						
P22	Denitrification deep ocean						
P23	Denitrification sediments						
P24	Denitrification surface ocean						
P25	Deposition of organics in coastal sediments						
P26	Deposition of organics in deep sediments						
P30	Export of inorganics to the oceans						-1.52E-02
P31	Export of organics to deep ocean						
P32	Export of soil organics to the oceans					-6.05E-03	
P33	Extracelluar release of organics						
P37	Geological transformation of kerogen						
P40	Lithification of inorganic P soils						-1.40E-02
P41	Litter decomposition				-1.35E-01	1.35E-01	
P42	Marine consumer production						
P43	Mortality of marine consumers						
P44	Mortality of marine producers						
P45	Mortality of zoomas			-8.91E-03	8.91E-03		
P50	Ocean NPP						
P51	Oceanic sea salt P emissions	3.10E-04					
P53	Other deep ocean detrital processing						
P55	Other sediments organic processing						
P56	Other soil processing					-1.29E-01	1.29E-01
P57	Other surface ocean detrital processing						
P58	Other zoomass processes		-1.45E-02	8.91E-03	5.57E-03		
P69	Release of PO_4^{3-} from sediments						
P71	Sedimentation of organic soils					-6.12E-08	
P72	Soil denitrification					-4.56E-04	4.56E-04
P74	Subduction						
P76	Terrestrial NPP (excl. crops)		1.76E-01		-4.40E-02		-1.32E-01
P78	Vegetation litterfall		-1.42E-01		1.42E-01		
P79	Weathering of crustal rocks						2.00E-02
P80	Wildfires		-1.35E-03		1.68E-03	-3.32E-04	
	Anthrosphere		-1.56E-02		2.06E-02	9.16E-04	8.19E-03
	Net stock change		1.96E-03				-3.91E-03

Table D.3 Phosphorus Cycle Flows (Cont.)

		7	8	9	10	11	12
		Landfilled solid waste P	Kerogen P	Coal P	Other lithosphere P	Ocean inorganic P	Marine photoautotrophs P
		P	P	$C_{131}N_2S_1P_{0.2}$	P	HPO_4^{3-}	$C_{108}N_{15.5}S_{1.3}P_1$
		Pg P	Pg P	Pg P	Pg P	Pg P	Pg P
P1	Aeolian emissions of PO_4^{3-} aerosols						
P5	Atmos. deposition of PO_4^{3-} aerosols					3.25E-04	
P19	Coal loss			-2.64E-08	6.78E-09		
P20	Deep burial of inorganic sediments				1.60E-02		
P21	Deep burial of organic sediments		5.78E-03				
P22	Denitrification deep ocean					4.83E-05	
P23	Denitrification sediments						
P24	Denitrification surface ocean					1.18E-03	
P25	Deposition of organics in coastal sediments						
P26	Deposition of organics in deep sediments						
P30	Export of inorganics to the oceans					6.18E-03	
P31	Export of organics to deep ocean						
P32	Export of soil organics to the oceans						
P33	Extracelluar release of organics						-2.26E-01
P37	Geological transformation of kerogen		-1.96E-08	1.96E-08			
P40	Lithification of inorganic P soils				1.40E-02		
P41	Litter decomposition						
P42	Marine consumer production					8.20E-01	-3.50E-01
P43	Mortality of marine consumers						
P44	Mortality of marine producers						-6.05E-01
P45	Mortality of zoomas						
P50	Ocean NPP					-1.18E+00	1.18E+00
P51	Oceanic sea salt P emissions					-3.10E-04	
P53	Other deep ocean detrital processing					1.43E-02	
P55	Other sediments organic processing						
P56	Other soil processing						
P57	Other surface ocean detrital processing					3.06E-01	
P58	Other zoomass processes						
P69	Release of PO_4^{3-} from sediments					3.39E-02	
P71	Sedimentation of organic soils		6.12E-08				
P72	Soil denitrification						
P74	Subduction		-2.30E-05		2.30E-05		
P76	Terrestrial NPP (excl. crops)						
P78	Vegetation litterfall						
P79	Weathering of crustal rocks				-2.00E-02		
P80	Wildfires						
	Anthrosphere	1.42E-02		-1.26E-02	-1.98E-02		
	Net stock change	1.42E-02	5.76E-03	-1.26E-02	-9.70E-03		

Table D.3 Phosphorus Cycle Flows (Cont.)

		13 Marine consumers P	14 Surface ocean dcmpsrs & organic P	15 Deep ocean dcmpsrs & other organic P	16 Marine sediments organic P	17 Marine sediments inorganic P	18 Anthrosphere P
		$C_{103}N_{16.5}S_{1.3}P_1$	P	P	P	PO_4^{3-}	P
		Pg P	Pg P	Pg P	Pg P	Pg P	Pg P
P1	Aeolian emissions of PO_4^{3-} aerosols						
P5	Atmos. deposition of PO_4^{3-} aerosols					7.59E-04	
P19	Coal loss						
P20	Deep burial of inorganic sediments					-1.60E-02	
P21	Deep burial of organic sediments				-5.78E-03		
P22	Denitrification deep ocean			-4.83E-05			
P23	Denitrification sediments				-3.36E-03	3.36E-03	
P24	Denitrification surface ocean		-1.18E-03				
P25	Deposition of organics in coastal sediments		-3.87E-02		3.87E-02		
P26	Deposition of organics in deep sediments			-3.71E-03	3.71E-03		
P30	Export of inorganics to the oceans					9.05E-03	
P31	Export of organics to deep ocean		-1.80E-02	1.80E-02			
P32	Export of soil organics to the oceans		2.62E-03		3.43E-03		
P33	Extracelluar release of organics		2.26E-01				
P37	Geological transformation of kerogen						
P40	Lithification of inorganic P soils						
P41	Litter decomposition						
P42	Marine consumer production	8.22E-01	-1.29E+00				
P43	Mortality of marine consumers	-8.22E-01	8.22E-01				
P44	Mortality of marine producers		6.05E-01				
P45	Mortality of zoomas						
P50	Ocean NPP						
P51	Oceanic sea salt P emissions						
P53	Other deep ocean detrital processing			-1.43E-02			
P55	Other sediments organic processing				-3.67E-02	3.67E-02	
P56	Other soil processing						
P57	Other surface ocean detrital processing		-3.06E-01				
P58	Other zoomass processes						
P69	Release of PO_4^{3-} from sediments					-3.39E-02	
P71	Sedimentation of organic soils						
P72	Soil denitrification						
P74	Subduction						
P76	Terrestrial NPP (excl. crops)						
P78	Vegetation litterfall						
P79	Weathering of crustal rocks						
P80	Wildfires						
	Anthrosphere	-2.65E-04					4.20E-03
	Net stock change						4.20E-03

Table D.4 Sulphur Cycle Flows

		1	2	3	4	5	6
		Atmospheric sulphate	S dioxide	C disulfide	Carbonyl sulfide	Hydrogen sulfide	Dimethyl sulfide
		SO_4^{2-}	SO_2	CS_2	OCS	H_2S	$(CH_3)_2S$
		Pg S	Pg S	Pg S	Pg S	Pg S	Pg S
S2	Aeolian emissions of SO_4^{2-} aerosols	8.00E-03					
S6	Atmos. deposition of SO_2		-2.09E-02				
S7	Atmos. deposition of SO_4^{2-}	-2.36E-01					
S8	Atmos. destruction of CS_2		1.73E-04	-3.46E-04	1.73E-04		
S9	Atmos. destruction of DMS		2.58E-02		9.07E-05		-2.59E-02
S10	Atmos. destruction of H_2S		9.28E-03			-9.28E-03	
S11	Atmos. destruction of OCS		1.84E-05		-9.36E-05	7.53E-05	
S19	Coal loss						
S20	Deep burial of inorganic sediments						
S21	Deep burial of organic sediments						
S22	Denitrification deep ocean						
S23	Denitrification sediments						
S24	Denitrification surface ocean						
S25	Deposition of organics in coastal sediments						
S26	Deposition of organics in deep sediments						
S27	Emissions from solid waste disposal sites						
S28	Excretion of H_2S by vegetation		-4.70E-05			4.70E-05	
S30	Export of inorganics to the oceans						
S31	Export of organics to deep ocean						
S32	Export of soil organics to the oceans						
S33	Extracelluar release of organics						2.40E-02
S36	Geological emissions of S gases		6.68E-03	4.21E-05	1.60E-04	2.60E-03	
S39	Hydrothermal sulfide deposition						
S41	Litter decomposition						
S42	Marine consumer production						
S43	Mortality of marine consumers						
S44	Mortality of marine producers						
S45	Mortality of zoomas						
S50	Ocean NPP						
S52	Oceanic sea salt SO_4^{2-} emissions	1.44E-01					
S53	Other deep ocean detrital processing						
S54	Other emissions from natural wetlands			1.30E-05	1.24E-05	1.46E-04	4.80E-05
S55	Other sediments organic processing					7.53E-04	
S56	Other soil processing			-2.25E-04	-3.94E-04	3.97E-04	1.50E-04
S57	Other surface ocean detrital processing			1.85E-04	1.95E-04	1.41E-03	
S58	Other zoomass processes						
S61	Oxidation of SO_2	8.38E-02	-8.38E-02				
S64	Petroleum loss						
S70	Release of SO_4^{2-} from sediments						
S71	Sedimentation of organic soils						
S72	Soil denitrification						
S74	Subduction						
S76	Terrestrial NPP (excl. crops)				-2.41E-04	2.41E-04	1.50E-03
S78	Vegetation litterfall						
S79	Weathering of crustal rocks						
S80	Wildfires		2.26E-04		3.28E-06		
	Anthrosphere		6.25E-02	3.31E-04	9.39E-05	3.61E-03	2.34E-04
	Net stock change						

Table D.4 Sulphur Cycle Flows (Cont.)

		7	8	9	10	11	12
		Vegetation S	Zoomas S	Litter/detritus S	Other soil organic matter S	Soil inorganic S	Landfilled solid waste S
		$C_{790}N_{7.6}S_{3.1}P_1$	$C_{115.8}N_{14.5}S_{0.2}P_1$	S	S	SO_4^{2-}	S
		Pg S	Pg S	Pg S	Pg S	Pg S	Pg S
S2	Aeolian emissions of SO_4^{2-} aerosols					-8.00E-03	
S6	Atmos. deposition of SO_2					6.91E-03	
S7	Atmos. deposition of SO_4^{2-}					8.03E-02	
S8	Atmos. destruction of CS_2						
S9	Atmos. destruction of DMS						
S10	Atmos. destruction of H_2S						
S11	Atmos. destruction of OCS						
S19	Coal loss				1.00E-07		
S20	Deep burial of inorganic sediments						
S21	Deep burial of organic sediments						
S22	Denitrification deep ocean						
S23	Denitrification sediments						
S24	Denitrification surface ocean						
S25	Deposition of organics in coastal sediments						
S26	Deposition of organics in deep sediments						
S27	Emissions from solid waste disposal sites						
S28	Excretion of H_2S by vegetation						
S30	Export of inorganics to the oceans					-2.25E-01	
S31	Export of organics to deep ocean						
S32	Export of soil organics to the oceans				-8.74E-03		
S33	Extracelluar release of organics						
S36	Geological emissions of S gases						
S39	Hydrothermal sulfide deposition						
S41	Litter decomposition			-4.94E-01	4.94E-01		
S42	Marine consumer production						
S43	Mortality of marine consumers						
S44	Mortality of marine producers						
S45	Mortality of zoomas		-1.86E-03	1.86E-03			
S50	Ocean NPP						
S52	Oceanic sea salt SO_4^{2-} emissions						
S53	Other deep ocean detrital processing						
S54	Other emissions from natural wetlands				-2.19E-04		
S55	Other sediments organic processing						
S56	Other soil processing				-4.85E-01	4.85E-01	
S57	Other surface ocean detrital processing						
S58	Other zoomas processes	-4.67E-02	1.86E-03	4.49E-02			
S61	Oxidation of SO_2						
S64	Petroleum loss				2.22E-08		
S70	Release of SO_4^{2-} from sediments						
S71	Sedimentation of organic soils				-5.99E-08		
S72	Soil denitrification				-1.89E-03	1.89E-03	
S74	Subduction						
S76	Terrestrial NPP (excl. crops)	5.64E-01		-9.89E-02		-4.67E-01	
S78	Vegetation litterfall	-4.57E-01		4.57E-01			
S79	Weathering of crustal rocks					7.35E-02	
S80	Wildfires	-4.32E-03		4.89E-03	-8.01E-04		
	Anthrosphere	-4.97E-02		8.36E-02	3.34E-03	-1.48E-02	4.08E-02
	Net stock change	6.29E-03				-6.67E-02	4.08E-02

Table D.4 Sulphur Cycle Flows (Cont.)

		13	14	15	16	17	18
		Kerogen S	Coal S	Petroleum S	Other lithosphere S	Ocean inorganic S	Marine photoautotrophs S
		S	$C_{131}N_2S_1P_{0.2}$	$C_{129}N_1S_1$	S	SO_4^{2-}	$C_{108}N_{15.5}S_{1.3}P_1$
		Pg S	Pg S	Pg S	Pg S	Pg S	Pg S
S2	Aeolian emissions of SO_4^{2-} aerosols						
S6	Atmos. deposition of SO_2					1.40E-02	
S7	Atmos. deposition of SO_4^{2-}					1.55E-01	
S8	Atmos. destruction of CS_2						
S9	Atmos. destruction of DMS						
S10	Atmos. destruction of H_2S						
S11	Atmos. destruction of OCS						
S19	Coal loss		-1.35E-07		3.47E-08		
S20	Deep burial of inorganic sediments				3.90E-02		
S21	Deep burial of organic sediments	4.20E-03					
S22	Denitrification deep ocean					2.01E-04	
S23	Denitrification sediments						
S24	Denitrification surface ocean					1.31E-03	
S25	Deposition of organics in coastal sediments						
S26	Deposition of organics in deep sediments						
S27	Emissions from solid waste disposal sites						
S28	Excretion of H_2S by vegetation						
S30	Export of inorganics to the oceans					2.25E-01	
S31	Export of organics to deep ocean						
S32	Export of soil organics to the oceans						
S33	Extracelluar release of organics						-3.08E-01
S36	Geological emissions of S gases				-9.48E-03		
S39	Hydrothermal sulfide deposition				9.60E-02	-9.60E-02	
S41	Litter decomposition						
S42	Marine consumer production					1.11E+00	-4.76E-01
S43	Mortality of marine consumers						
S44	Mortality of marine producers						-8.23E-01
S45	Mortality of zoomas						
S50	Ocean NPP					-1.61E+00	1.61E+00
S52	Oceanic sea salt SO_4^{2-} emissions					-1.44E-01	
S53	Other deep ocean detrital processing					8.26E-03	
S54	Other emissions from natural wetlands						
S55	Other sediments organic processing						
S56	Other soil processing						
S57	Other surface ocean detrital processing					3.86E-01	
S58	Other zoomas processes						
S61	Oxidation of SO_2						
S64	Petroleum loss			-2.92E-08	7.08E-09		
S70	Release of SO_4^{2-} from sediments					4.09E-02	
S71	Sedimentation of organic soils	5.99E-08					
S72	Soil denitrification						
S74	Subduction	-1.18E-04			1.18E-04		
S76	Terrestrial NPP (excl. crops)						
S78	Vegetation litterfall						
S79	Weathering of crustal rocks				-7.35E-02		
S80	Wildfires						
	Anthrosphere		-6.43E-02	-6.41E-02	-3.76E-02		
	Net stock change	4.09E-03	-6.43E-02	-6.41E-02	1.45E-02	9.31E-02	

Table D.4 Sulphur Cycle Flows

		19 Marine consumers S	20 Surface ocean dcmpsrs & organic S	21 Deep ocean dcmpsrs & other organic S	22 Marine sediments organic S	23 Marine sediments inorganic S	24 Anthrosphere S
		$C_{103}N_{16.5}S_{1.3}P_1$	S	S	S	S	S
		Pg S	Pg S	Pg S	Pg S	Pg S	Pg S
S2	Aeolian emissions of SO_4^{2-} aerosols						
S6	Atmos. deposition of SO_2						
S7	Atmos. deposition of SO_4^{2-}						
S8	Atmos. destruction of CS_2						
S9	Atmos. destruction of DMS						
S10	Atmos. destruction of H_2S						
S11	Atmos. destruction of OCS						
S19	Coal loss						
S20	Deep burial of inorganic sediments					-3.90E-02	
S21	Deep burial of organic sediments				-4.20E-03		
S22	Denitrification deep ocean			-2.01E-04			
S23	Denitrification sediments				-5.58E-03	5.58E-03	
S24	Denitrification surface ocean		-1.31E-03				
S25	Deposition of organics in coastal sediments		-8.33E-02		8.33E-02		
S26	Deposition of organics in deep sediments			-1.57E-03	1.57E-03		
S27	Emissions from solid waste disposal sites						
S28	Excretion of H_2S by vegetation						
S30	Export of inorganics to the oceans						
S31	Export of organics to deep ocean		-1.00E-02	1.00E-02			
S32	Export of soil organics to the oceans		8.74E-03				
S33	Extracelluar release of organics		2.84E-01				
S36	Geological emissions of S gases						
S39	Hydrothermal sulfide deposition						
S41	Litter decomposition						
S42	Marine consumer production	1.11E+00	-1.74E+00				
S43	Mortality of marine consumers	-1.11E+00	1.11E+00				
S44	Mortality of marine producers		8.23E-01				
S45	Mortality of zoomas						
S50	Ocean NPP						
S52	Oceanic sea salt SO_4^{2-} emissions						
S53	Other deep ocean detrital processing			-8.26E-03			
S54	Other emissions from natural wetlands						
S55	Other sediments organic processing				-7.51E-02	7.43E-02	
S56	Other soil processing						
S57	Other surface ocean detrital processing		-3.88E-01				
S58	Other zoomas processes						
S61	Oxidation of SO_2						
S64	Petroleum loss						
S70	Release of SO_4^{2-} from sediments					-4.09E-02	
S71	Sedimentation of organic soils						
S72	Soil denitrification						
S74	Subduction						
S76	Terrestrial NPP (excl. crops)						
S78	Vegetation litterfall						
S79	Weathering of crustal rocks						
S80	Wildfires						
	Anthrosphere	-3.56E-04					3.63E-02
	Net stock change						3.63E-02

Table D.5 Concordance Mapping Within Environment Biogeochemical Flows Definitions between Chapters 5, 6 and 8

	Chapters 5 Within Environment Flow Names	Chapter 6 Ecotime Analysis Flow Names[1]	Chapter 8 DGBCM Short Flow Names	Chapter 8 DGBCM Flow Names
1 P	Aeolian emissions of PO_4^{3-} aerosols	N/A	psem	PO_4^{3-} soil emissions
2 S	Aeolian emissions of SO_4^{2-} aerosols	Aeolian emissions of SO_4^{2-} aerosols	stem	Aeolian emissions of SO_4^{2-} aerosols
3 N	Atmos. deposition of NH_3	Atmos. deposition of NH_3	ndep	Atmos. deposition of N
4 N	Atmos. deposition of NO_3^-	Atmos. deposition of NO_3^-	ndep	Atmos. deposition of N
5 P	Atmos. deposition of PO_4^{3-} aerosols[2]	Atmos. deposition of PO_4^{3-} aerosols[2]	poem	PO_4^{3-} ocean emissions
5 P	Atmos. deposition of PO_4^{3-} aerosols[2]	N/A	psem	PO_4^{3-} soil emissions
6 S	Atmos. deposition of SO_2	N/A	sdep	Atmos. deposition of S
7 S	Atmos. deposition of SO_4^{2-}	N/A	sdep	Atmos. deposition of S
8 C,S	Atmos. destruction of CS_2	N/A	N/A	N/A
9 C,S	Atmos. destruction of DMS	Atmos. destruction of DMS	N/A	N/A
10 S	Atmos. destruction of H_2S	N/A	N/A	N/A
11 C,S	Atmos. destruction of OCS	N/A	N/A	N/A
12 C	$CaCO_3$ deposition in deep sediments	N/A	N/A	N/A
13 C	$CaCO_3$ dissolution in deep ocean	N/A	occr	Remineralisation of $CaCO_3$
14 C	$CaCO_3$ dissolution in deep sediments	N/A	occr	Remineralisation of $CaCO_3$
15 C	$CaCO_3$ dissolution in surface ocean	N/A	occr	Remineralisation of $CaCO_3$
16 C	$CaCO_3$ production by consumers	Ocean $CaCO_3$ production	occp	$CaCO_3$ production
17 C	$CaCO_3$ production by producers	Ocean $CaCO_3$ production	occp	$CaCO_3$ production
18 C	CH4 emissions from natural wetlands	N/A	csol	Other C soil processing
19 C,N,P,S	Coal loss	N/A	losc	Coal loss
20 C	Deep burial of inorganic sediments	N/A	cibr	Deep burial of $CaCO_3$ sediments
20 N	Deep burial of inorganic sediments	N/A	nibr	Deep burial of inorganic N sediments
20 P	Deep burial of inorganic sediments	N/A	pibr	Deep burial of inorganic P sediments
20 S	Deep burial of inorganic sediments	N/A	sibr	Deep burial of inorganic S sediments
21 C	Deep burial of organic sediments	N/A	cobr	Deep burial of organic C sediments
21 N	Deep burial of organic sediments	N/A	nobr	Deep burial of organic N sediments
21 P	Deep burial of organic sediments	N/A	pobr	Deep burial of organic P sediments
21 S	Deep burial of organic sediments	N/A	sobr	Deep burial of organic S sediments
22 N	Denitrification deep ocean	Ocean denitrification	oden	Ocean denitrification
23 N	Denitrification sediments	N/A	oden	Ocean denitrification
24 N	Denitrification surface ocean	Ocean denitrification	oden	Ocean denitrification
25 C,N,P,S	Deposition of organics in coastal sediments	Deposition of organics sediments	N/A	N/A
26 C,N,P,S	Deposition of organics in deep sediments	Deposition of organics sediments	N/A	N/A
27 C	Emissions from solid waste disposal sites	N/A	N/A	N/A
28 S	Excretion of H_2S by vegetation	N/A	N/A	N/A
29 C	Export of $CaCO_3$ to deep ocean	N/A	N/A	N/A
30 C	Export of inorganics to the oceans	River export	cexp	Export of C to the oceans
30 N	Export of inorganics to the oceans	River export	nexp	Export of N to the oceans
30 P	Export of inorganics to the oceans	River export	pexp	Export of P to the oceans
30 S	Export of inorganics to the oceans	River export	sexp	Export of S to the oceans
31 C,N,P,S	Export of organics to deep ocean	N/A	N/A	N/A
32 C	Export of soil organics to the oceans	River export	cexp	Export of C to the oceans
32 N	Export of soil organics to the oceans	River export	nexp	Export of N to the oceans
32 P	Export of soil organics to the oceans	River export	pexp	Export of P to the oceans
32 S	Export of soil organics to the oceans	River export	sexp	Export of S to the oceans
33 C	Extracelluar release of organics	N/A	cexc	C extracelluar release

Table D.5 Concordance Mapping Within Environment Biogeochemical Flows Definitions between Chapters 5, 6 and 8 (Cont.)

	Chapters 5 Within Environment Flow Names	Chapter 6 Ecotime Analysis Flow Names[1]	Chapter 8 DGBCM Short Flow Names	Chapter 8 DGBCM Flow Names
33 N	Extracelluar release of organics	N/A	nexc	N extracelluar release
33 P	Extracelluar release of organics	N/A	pexc	P extracelluar release
33 S	Extracelluar release of organics	N/A	sexc	S extracelluar release
34 C	Geological emissions of CH_4	N/A	geme	Geological emissions of CH_4
35 C	Geological emissions of CO_2	N/A	gecd	Geological emissions of CO_2
36 S	Geological emissions of S gases	N/A	gesg	Geological emissions of S gases
37 C,N,P,S	Geological transformation of kerogen	N/A	fffm	Geological transformation of kerogen
38 C	Hydrothermal inputs of $CaCO_3$	N/A	hdcc	Hydrothermal inputs of $CaCO_3$
39 S	Hydrothermal sulfide deposition	N/A	sibr	Deep burial of inorganic S sediments
40 P	Lithification of inorganic P soils	N/A	plit	Lithification of inorganic P soils
41 C	Litter decomposition	Litter decomposition	crot	C litter decomposition
41 N	Litter decomposition	Litter decomposition	nrot	N litter decomposition
41 P	Litter decomposition	Litter decomposition	prot	P litter decomposition
41 S	Litter decomposition	Litter decomposition	srot	S litter decomposition
42 C,N,P,S	Marine consumer production	N/A	ocpr	Marine consumer production
43 C	Mortality of marine consumers	N/A	como	C mortality of marine prdcrs & cnsmrs
43 N	Mortality of marine consumers	N/A	nomo	N mortality of marine prdcrs & cnsmrs
43 P	Mortality of marine consumers	N/A	pomo	P mortality of marine prdcrs & cnsmrs
43 S	Mortality of marine consumers	N/A	somo	S mortality of marine prdcrs & cnsmrs
44 C	Mortality of marine producers	N/A	como	C mortality of marine prdcrs & cnsmrs
44 N	Mortality of marine producers	N/A	nomo	N mortality of marine prdcrs & cnsmrs
44 P	Mortality of marine producers	N/A	pomo	P mortality of marine prdcrs & cnsmrs
44 S	Mortality of marine producers	N/A	somo	S mortality of marine prdcrs & cnsmrs
45 C	Mortality of zoomas	N/A	ctmo	C terrestrial litterfall & mortality
45 N	Mortality of zoomas	N/A	ntmo	N terrestrial litterfall & mortality
45 P	Mortality of zoomas	N/A	ptmo	P terrestrial litterfall & mortality
45 S	Mortality of zoomas	N/A	stmo	S terrestrial litterfall & mortality
46 N	N_2 fixation by lightning	N_2 fixation by lightning	afix	N_2 fixation by lightning
47 C	Natural gas loss	N/A	geme	Geological emissions of CH_4
48 C	Net $CaCO_3$ deposition in coastal sediments	Net $CaCO_3$ deposition in coastal sediments	N/A	N/A
49 N	NH3-hydroxyl reaction	N/A	N/A	N/A
50 C,N,P,S	Ocean NPP	Ocean NPP	onpp	Ocean NPP
51 P	Oceanic sea salt P emissions	N/A	poem	PO_4^{3-} ocean emissions
52 S	Oceanic sea salt SO_4^{2-} emissions	N/A	soem	Oceanic sea salt SO_4^{2-} emissions
53 C	Other deep ocean detrital processing	Other ocean detrital processing	corg	Organic matter C processing
53 N	Other deep ocean detrital processing	Other ocean detrital processing	norg	Organic matter N processing
53 P	Other deep ocean detrital processing	Other ocean detrital processing	porg	Organic matter P processing
53 S	Other deep ocean detrital processing	Other ocean detrital processing	sorg	Organic matter S processing
54 C	Other emissions from natural wetlands	N/A	csol	Other soil C processing
54 S	Other emissions from natural wetlands	N/A	ssol	Other soil S processing
55 C	Other sediments organic processing	N/A	corg	Organic matter C processing
55 N	Other sediments organic processing	N/A	norg	Organic matter N processing
55 P	Other sediments organic processing	N/A	porg	Organic matter P processing
55 S	Other sediments organic processing	N/A	sorg	Organic matter S processing
56 C	Other soil processing	N/A	csol	Other soil C processing

Table D.5 Concordance Mapping Within Environment Biogeochemical Flows Definitions between Chapters 5, 6 and 8 (Cont.)

	Chapters 5 Within Environment Flow Names	Chapter 6 Ecotime Analysis Flow Names[1]	Chapter 8 DGBCM Short Flow Names	Chapter 8 DGBCM Flow Names
56 N	Other soil processing	N/A	nsol	Other soil N processing
56 S	Other soil processing	N/A	ssol	Other soil S processing
57 C	Other surface ocean detrital processing	Other ocean detrital processing	corg	Organic matter C processing
57 N	Other surface ocean detrital processing	Other ocean detrital processing	norg	Organic matter N processing
57 P	Other surface ocean detrital processing	Other ocean detrital processing	porg	Organic matter P processing
57 S	Other surface ocean detrital processing	Other ocean detrital processing	sorg	Organic matter S processing
58 C	Other zoomass processes	N/A	czpr	C other zoomass processes
58 N	Other zoomass processes	N/A	nzpr	N other zoomass processes
58 P	Other zoomass processes	N/A	pzpr	P other zoomass processes
58 S	Other zoomass processes	N/A	szpr	S other zoomass processes
59 C	Oxidation of CH_4	Oxidation of CH_4 to CO	N/A	N/A
60 C	Oxidation of CO	Oxidation of CO to CO_2	N/A	N/A
61 S	Oxidation of SO_2	Oxidation of SO_2	N/A	N/A
62 C	Oxidation of VOCs to CO	N/A	N/A	N/A
63 C	Oxidation of VOCs to CO_2	Oxidation of VOC to CO_2	N/A	N/A
64 C,N,S	Petroleum loss	N/A	losp	Petroleum loss
65 C	Release of CH_4 from hydrates	N/A	geme	Geological emissions of CH_4
66 C	Release of CO_2 from the oceans	Release of CO_2 from the oceans	cdrl	Release of CO_2 from the oceans
67 N	Release of NO_3^- from sediments	N/A	N/A	N/A
68 N	Release of NO_x from soils	Release of NO_x from soils	tnox	Release of NO_x from soils
69 P	Release of PO_4^{3-} from sediments	N/A	N/A	N/A
70 S	Release of SO_4^{2-} from sediments	N/A	N/A	N/A
71 C	Sedimentation of organic soils	N/A	ctse	Sedimentation of organic C in soils
71 N	Sedimentation of organic soils	N/A	ntse	Sedimentation of organic N in soils
71 P	Sedimentation of organic soils	N/A	ptse	Sedimentation of organic P in soils
71 S	Sedimentation of organic soils	N/A	stse	Sedimentation of organic S in soils
72 N	Soil denitrification	Soil denitrification	tden	Soil denitrification
73 N	Stratospheric destruction of N_2O	Stratospheric destruction of N_2O	arnl	Stratospheric destruction of N_2O
74 C,N,P,S	Subduction	N/A	N/A	N/A
75 N	Terrestrial N_2 fixation (excl. agriculture)	Terrestrial N_2 fixation (excl. agriculture)	tfix	Terrestrial N_2 fixation (excl. agriculture)
76 C,N,P,S	Terrestrial NPP (excl. crops)	Terrestrial NPP (excl. crops)	tnpp	Terrestrial NPP (excl. crops)
77 C	Uptake of CO_2 by the oceans	Uptake of CO_2 by the oceans	cdup	Uptake of CO_2 by the oceans
78 C	Vegetation litterfall	N/A	ctmo	C terrestrial litterfall & mortality
78 N	Vegetation litterfall	N/A	ntmo	N terrestrial litterfall & mortality
78 P	Vegetation litterfall	N/A	ptmo	P terrestrial litterfall & mortality
78 S	Vegetation litterfall	N/A	stmo	S terrestrial litterfall & mortality
79 C	Weathering of crustal rocks	N/A	cwet	Weathering of C crustal rocks
79 N	Weathering of crustal rocks	N/A	nwet	Weathering of N crustal rocks
79 P	Weathering of crustal rocks	N/A	pwet	Weathering of P crustal rocks
79 S	Weathering of crustal rocks	N/A	swet	Weathering of S crustal rocks
80 C	Wildfires[3]	N/A	cwfs	C soil wildfires
80 N	Wildfires[3]	N/A	nwfs	N soil wildfires
80 P	Wildfires[3]	N/A	pwfs	P soil wildfires
80 S	Wildfires[3]	N/A	swfs	S soil wildfires
80 C,N,P,S	Wildfires[3]	N/A	wfve	Vegetation wildfires

Appendix E

Environmental Commodity Stocks

This Appendix presents the environmental commodity stocks utilised in Chapters 4, 5, 6, 8 and 9. Specifically, in Tables E.1–E.4 the environmental commodity stocks for C, N, P and S are presented. Table E.5 provides a concordance mapping the environmental commodity stocks between chapters, while Table E.6 concords the reporting aggregated environment commodity stocks used in Figures 4.1–4.4 with the full set of environment commodity stocks.

Table E.1 Carbon Stocks

Stock	Pg C	Reference	Pg C	Reference	Pg C	Reference	Pg C	Reference	This Study Pg C
C dioxide	7.50E+02	Schimel *et al*. (1995)	7.85E+02	Janzen (2004)	7.80E+02	Houghton (2005)	8.00E+02	Hermann (2006)	7.85E+02
Methane[1]	4.20E+00	Schlesinger (1997)							4.20E+00
Other atmosphere C[1]	2.18E-01	Schlesinger (1997)							2.18E-01
Volatile organic C[1]	1.68E-03	Schlesinger (1997)							1.68E-03
Vegetation C	6.52E+02	Saugier *et al*. (2000)[2]	5.60E+02	Schimel *et al*. (1995)[2]	6.54E+02	Mooney *et al*. (2001)[2]	4.66E+02	Prentice *et al*. (2001)[2]	6.48E+02
Zoomas C	7.05E-01	Smil (2000)							7.05E-01
Litter/detritus C	2.00E+02	Potter *et al*. (1993)	3.00E+02	Houghton (2005)	3.00E+02	Prentice *et al*. (2001)			3.00E+02
Soil C	3.19E+03	Field & Raupach (2004)[3]	2.22E+03	Prentice *et al*. (2001)	1.46E+03	Schlesinger (1997)	1.20E+03	Houhgton (2005)	2.89E+03
Marine photoautotrophs C[4]	3.00E+00	Houghton (2005)	3.00E+00	Hall & Scurlock (1993)	3.00E+00	Siegenthaler & Sarmiento (1993)			2.00E+00
Marine consumers C[4]	3.00E+00	Houghton (2005)	3.00E+00	Hall & Scurlock (1993)	3.00E+00	Siegenthaler & Sarmiento (1993)			1.00E+00
Ocean humus C	1.00E+03	Houghton (2005)[5]	1.03E+03	Holmen (1992)[6]	1.00E+03	Falkowski (2000)	7.70E+02	Lavelle *et al*. (2005)	1.03E+03
Ocean calcium carbonates	1.29E+03	Bowen (1979)							1.29E+03
Other ocean inorganic C	3.70E+04	Smil (2002)	3.70E+04	Houghton (2005)	3.66E+04	Sarmiento & Gruber (2006)[7]	3.74E+04	Falkowski (2000)[8]	3.65E+04
Marine sediments org C	3.00E+01	Den Elzen *et al*. (1995)							3.00E+01
Marine sediments inorg C	1.20E+02	Den Elzen *et al*. (1995)							1.20E+02
Carbonate minerals	6.25E+07	Mackenzie *et al*. (1993)	7.00E+07	Holmen (1992)					6.25E+07
Coal C	8.10E+03	Hermann (2006)	3.69E+03	Sundquist & Visser (2005)	3.76E+03	Falkowski *et al*. (2000)[9]	4.00E+03	Lal (2000)	3.69E+03
Kerogen C	1.25E+07	Sundquist & Visser (2005)[10]							1.25E+07
Natural gas C	8.30E+02	Hermann (2006)	5.00E+02	Lal (2000)	1.40E+02	Falkowski *et al*. (2000)	5.24E+02	Sundquist & Visser (2005)	5.24E+02
Petroleum C	2.25E+03	Hermann (2006)	5.00E+02	Lal (2000)	2.30E+02	Falkowski *et al*. (2000)[9]	7.39E+02	Sundquist & Visser (2005)	7.39E+02
Other lithosphere C[11]	3.24E+07	Sundquist & Visser (2005)							3.24E+07

Notes: 1. Based on residence times, 2. includes crops, 3 includes litter, 4. includes all ocean biota, 5. dissolved organic C only, 6. 1000 Pg C for dissolved organic C, 30 Pg C for particulate organic C, 7. dissolved inorganic C ocean concentration of 0.002255 mol/kg and ocean mass of 1.35 x 10^21 kg, 8. includes $CaCO_3$, 9. includes peat, 10. includes organic C in fossil fuels, and 11. includes mantle C.

Table E.2 Nitrogen Stocks

Stock	Pg N	Reference	Pg N	Reference	Pg N	Reference	Pg N	Reference	This Study Pg N
Dinitrogen	3.87E+06	Schlesinger (1997)	3.90E+06	Söderlund & Svensson (1976)	3.95E+06	Lavelle *et al*. (2005)	3.95E+06	Mackenzie (1998)	3.87E+06
N oxides[1]	1.38E-04	Schlesinger (1997)							1.38E-04
Nitrous oxide[1]	1.70E+00	Schlesinger (1997)							1.70E+00
Ammonia/ammonium[1]	8.73E-04	Schlesinger (1997)							8.73E-04
Vegetation N[2]	1.00E+01	McElroy (1976)	1.25E+01	Söderlund & Svensson (1976)	3.50E+00	Schlesinger (1991)	3.50E+01	Lavelle *et al*. (2005)	7.27E+00
Zoomas N[3]									1.03E-01
Litter/detritus N[4]									3.77E+00
Soil N	9.50E+01	Post *et al*. (1985)	7.00E+01	McElroy *et al*. (1976)	9.50E+01	Lavelle *et al*. (2005)			9.50E+01
Marine photoautotrophs N[5]									3.35E-01
Marine consumers N[6]									1.46E-01
Ocean humus N[7]									1.65E+02
Ocean inorganic N	5.78E+02	Söderlund & Svensson (1976)	5.82E+02	Sarmiento & Gruber (2006)[8]	5.70E+02	Mackenzie (1998)	5.70E+02	McElroy (1976)	5.82E+02
Marine sediments org N	2.50E+00	Den Elzen *et al*. (1995)							2.50E+00
Marine sediments inorg N	3.98E+02	Den Elzen *et al*. (1995)							3.98E+02
Coal N[9]									6.33E+01
Kerogen N[10]									1.97E+05
Petroleum N[11]									2.93E+00
Other lithosphere N[12]	1.64E+08	Pierzynski *et al*. (2000)	1.90E+08	den Elzen *et al*. (1995)					1.72E+08

Notes: 1. Based on residence time, 2. from vegetation C stock with stoichiometry 306C:3.4N:1P:3.2S, 3. from zoomass C stock with stoichiometry 44.9C:6.5N:1P:0.2S, 4. from litter C stock with stoichiometry 44.1C:0.6N:0.2P:0.5S, 5. from photoautotrophs C stock with stoichiometry 41.9C:7N:1P:1.3S, 6. from marine consumers C stock with stoichiometry 39.9C:7.5N:1P:1.3S, 7. from organic matter C stock with stoichiometry 45.3C:7.2N:1P:1.3S, 8. ocean NO_3^- content given a concentration of 0.031 mol/m^3, 9. from coal C stock with stoichiometry 50.9C:0.9N:1P:0.2S, 10. based on kerogen C stock (less C in CH_4 hydrate) and lignite stoichiometry 82.3C:1.3N:1P:1.0S, 11. from petroleum C stock with stoichiometry 252C:1N:5.25S, and 12. based on Pierzynski *et al*. (2000), plus mantle N derived from mantle C stock from Sundquist & Visserm (2005) and N:C ratio from McDonough & Sun (1995).

Table E.3 Phosphorus Stocks

Stock	Pg P	Reference	Pg P	Reference	Pg P	Reference	Pg P	Reference	This Study Pg P
Phosphate aerosols	3.00E-05	Janke (1992)	2.80E-05	Lavelle *et al*. (2005)	3.00E-05	Ruttenberg (2005)			2.80E-05
Vegetation P[1]	3.00E+00	Ruttenberg (2005)	3.00E+00	Janke (1992)	3.00E+00	Mackenzie *et al*. (1993)	3.00E+00	Lerman *et al*. (1975)	2.12E+00
Zoomas P[2]									1.57E-02
Litter/detritus P[3]									1.08E+00
Soil P	2.00E+02	Jahnke (1992)[4]	2.00E+02	Lavelle *et al*. (2005)[4]	2.00E+02	Janke (1992)[4]			1.99E+02
Marine photoautotrophs P[5]									4.78E-02
Marine consumers P[6]									2.50E-02
Ocean humus P[7]									2.28E+01
Ocean inorganic P	9.01E+01	Sarmiento & Gruber (2006)[8]	9.00E+01	Janke (1992)	8.65E+01	Mackenzie *et al*. (1993)	9.00E+01	den Elzen *et al*. (1995)	9.01E+01
Marine sediments org P	3.87E-01	Lavelle *et al*. (2005)							3.87E-01
Marine sediments inorg P	4.00E+06	Lavelle *et al*. (2005)							4.00E+06
Coal P[9]									7.24E+01
Kerogen P[10]									1.52E+05
Other lithosphere P[11]									1.95E+09

Notes: 1. From vegetation C stock with stoichiometry 306C:3.4N:1P:3.2S, 2. from zoomass C stock with stoichiometry 44.9C:6.5N:1P:0.2S, 3. from litter C stock with stoichiometry 44.1C:0.6N:0.2P:0.5S, 4. includes litter P, 5. from photoautotrophs C stock with stoichiometry 41.9C:7N:1P:1.3S, 6. from marine consumers C stock with stoichiometry 39.9C:7.5N:1P:1.3S, 7. from organic matter C stock with stoichiometry 45.3C:7.2N:1P:1.3S, 8. ocean PO_4^{3-} content given a concentration of 0.00217 mol/m^3, 9. from coal C stock with stoichiometry 50.9C:0.9N:1P:0.2S, 10. based on C stock for kerogen (less C in CH_4 hydrate) with lignite stoichiometry 82.3C:1.3N:1P:1.0S, and 11. based on Lavelle *et al*. (2005), plus mantle P based on the mantle C stock from Sundquist & Visser (2005) and P:C ratio from McDonough & Sun (1995).

Table E.4 Sulphur Stocks

Stock	Pg S	Reference	Pg S	Reference	Pg S	Reference	Pg S	Reference	This Study Pg S
Atmospheric sulphate	2.80E-03	Schlesinger (1997)[1]	4.80E-03	Charlson *et al*. (1992)[1]	4.80E-03	Lavelle *et al*. (2005)[1]			9.14E-05
S dioxide[2]	8.38E-04	Schlesinger (1997)							8.38E-04
C disulfide[2]	6.09E-05	Schlesinger (1997)							6.09E-05
Carbonyl sulfide[2]	3.64E-03	Schlesinger (1997)							3.64E-03
Hydrogen sulfide[2]	9.90E-05	Schlesinger (1997)							9.90E-05
Dimethyl sulfide[2]	6.91E-05	Schlesinger (1997)							6.91E-05
Vegetation S[3]	9.20E+00	Bowen (1979)	9.00E+00	Mackenzie *et al*. (1993)	7.60E+00	Ayres (1996)			6.79E+00
Zoomas S[4]									3.28E-03
Litter/detritus S[5]									3.46E+00
Soil S	3.00E+02	Charlson *et al*. (1992)[6]	3.00E+02	Lavelle *et al*. (2005)[7]					2.97E+02
Marine photoautotrophs S[8]									6.43E-02
Marine consumers S[9]									3.37E-02
Ocean humus S[10]									3.06E+01
Ocean inorganic S	1.28E+06	Schlesinger (1997)	1.30E+06	Charlson *et al*. (1992)	1.30E+06	Lavelle *et al*. (2005)	1.30E+06	den Elzen *et al*. (1995)	1.28E+06
Marine sediments org S	5.21E-01	Charlson *et al*. (1992)	5.21E-01	Lavelle *et al*. (2005)					5.21E-01
Marine sediments inorg S	3.00E+05	Charlson *et al*. (1992)	3.00E+05	Lavelle *et al*. (2005)					3.00E+05
Coal S[11]									1.52E+01
Kerogen S[12]									1.55E+05
Petroleum S[13]									1.53E+01
Other lithosphere S[14]	2.03E+07	Charlson *et al*. (1992)[15]	2.43E+07	Lavelle *et al*. (2005)[15]	2.00E+07	den Elzen *et al*. (1995)[15]			1.35E+08

Notes: 1. Total atmospheric S, 2. based on residence time, 3. from vegetation C stock with stoichiometry 306C:3.4N:1P:3.2S, 4. from zoomass C stock with stoichiometry 44.9C:6.5N:1P:0.2S, 5. from litter C stock with stoichiometry 44.1C:0.6N:0.2P:0.5S, 6. total S in soils and freshwater, 7. total soil S, 8. from photoautotrophs C stock with stoichiometry 41.9C:7N:1P:1.3S, 9. from marine consumers C stock with stoichiometry 39.9C:7.5N:1P:1.3S, 10. from organic matter C stock with stoichiometry 45.3C:7.2N:1P:1.3S, 11. from coal C stock with stoichiometry 50.9C:0.9N:1P:0.2S, 12. based on kerogen C stock (less C in CH_4 hydrate) with lignite stoichiometry 82.3C:1.3N:1P:1.0S, 13. from petroleum C stock with stoichiometry 252C:1N:5.25S, 14. based on Charlson *et al*. (2000), plus mantle S based on the mantle C stock from Sundquist & Visser (2005) and S:C ratio from McDonough and Sun (1995), and 15. includes ocean sediments.

Table E.5 Concordance Mapping Environment Commodity Stocks between Chapters

Cycle	Sphere	Chemical Formula	Stock Name - Chapters 4 and 5 (Within Env. & between Env. & Economy)	Stock Name - Chapter 6 (Ecotime Analysis)	Stock Name - Chapter 8 (DGBCM)
C	Atmosphere	CO_2	C dioxide	C dioxide	AtmosnecC
C	Atmosphere	CH_4	Methane	Methane	AtmosnecC
C	Atmosphere	CO	C monoxide	Other atmosphere C	AtmosnecC
C	Atmosphere	C_xH_x	Volatile organic C	Volatile organic C	AtmosnecC
C	Atmosphere	COS	Carbonyl sulfide C	Other atmosphere C	AtmosnecC
C	Atmosphere	CS_2	C disulfide	Other atmosphere C	AtmosnecC
C	Atmosphere	$(CH_3)_2S$	Dimethyl sulfide C	Other atmosphere C	AtmosnecC
C	Terrestrial biosphere	$C_{790}N_{7.6}S_{3.1}P_1$	Vegetation C	Vegetation C	VegezoomasC
C	Terrestrial biosphere	$C_{115.8}N_{14.5}S_{0.2}P_1$	Zoomas C	Zoomass C	VegezoomasC
C	Terrestrial biosphere	C	Litter/detritus C	Litter/detritus C	DetritusC
C	Terrestrial biosphere	C	Other soil organic matter C	Soil C	SoilC
C	Terrestrial biosphere	CO_3^{2-}	Soil inorganic C	Soil C	SoilC
C	Terrestrial biosphere	C	Landfilled solid waste C	N/A	N/A
C	Lithosphere	C	Kerogen C	Kerogen C	LithosphereC
C	Lithosphere	C	Kerogen C	Kerogen C	GasC
C	Lithosphere	$C_{131}N_2S_1P_{0.2}$	Coal C	Coal C	CoalC
C	Lithosphere	$C_{129}N_1S_1$	Petroleum C	Petroleum C	PetroleumC
C	Lithosphere	$C_nH_{(2n+2)}$	Natural gas C	Natural gas C	GasC
C	Lithosphere	$CO3^-$	Carbonate minerals	Carbonate minerals	LithosphereC
C	Lithosphere	C	Other lithosphere C	Other lithosphere C	LithosphereC
C	Oceans	HCO_3^-	Other ocean inorganic C	Other ocean inorganic C	OceannecC
C	Oceans	$C_{108}N_{15.5}S_{1.3}P_1$	Marine photoautotrophs C	Marine photoautotrophs C	OceanpandcC
C	Oceans	$C_{103}N_{16.5}S_{1.3}P_1$	Marine consumers C	Marine consumers C	OceanpandcC
C	Oceans	C	Surface ocean dcmpsrs & organic C	Ocean humus C	OceanhumusC
C	Oceans	$CaCO_3$	Surface ocean calcium carbonates	Ocean calcium carbonates	OceancalccarbC
C	Oceans	C	Deep ocean dcmpsrs & other organic C	Ocean humus C	OceanhumusC
C	Oceans	$CaCO_3$	Deep ocean calcium carbonates	Ocean calcium carbonates	OceancalccarbC
C	Oceans	C	Marine sediments organic C	Marine sediments C	OceanhumusC
C	Oceans	$CaCO_3$	Marine sediments calcium carbonates	Marine sediments C	OceancalccarbC
N	Atmosphere	N_2	Dinitrogen	Dinitrogen	Atmosn2N
N	Atmosphere	NO_x	N oxides	N oxides	AtmosnecN
N	Atmosphere	N_2O	Nitrous oxide	Nitrous oxide	AtmosnecN
N	Atmosphere	NH_3/ NH_4^+	Ammonia/ammonium	Ammonia/ammonium	AtmosnecN
N	Terrestrial biosphere	$C_{790}N_{7.6}S_{3.1}P_1$	Vegetation N	Vegetation N	VegezoomasN
N	Terrestrial biosphere	$C_{115.8}N_{14.5}S_{0.2}P_1$	Zoomas N	Zoomass N	VegezoomasN
N	Terrestrial biosphere	N	Litter/detritus N	Litter/detritus N	DetritusN
N	Terrestrial biosphere	N	Other soil organic matter N	Soil N	SoilN
N	Terrestrial biosphere	NO_3^-/NH_4+	Soil inorganic N	Soil N	SoilN
N	Terrestrial biosphere	N	Landfilled solid waste N	N/A	N/A
N	Lithosphere	N	Kerogen N	Kerogen N	LithosphereN
N	Lithosphere	$C_{131}N_2S_1P_{0.2}$	Coal N	Coal N	CoalN
N	Lithosphere	$C_{129}N_1S_1$	Petroleum N	Petroleum N	PetroleumN
N	Lithosphere	N	Other lithosphere N	Other lithosphere N	LithosphereN
N	Oceans	NO_3^-/NH_4+	Ocean inorganic N	Ocean inorganic N	OceannecN
N	Oceans	$C_{108}N_{15.5}S_{1.3}P_1$	Marine photoautotrophs N	Marine photoautotrophs N	OceanpandcN
N	Oceans	$C_{103}N_{16.5}S_{1.3}P_1$	Marine consumers N	Marine consumers N	OceanpandcN
N	Oceans	N	Surface ocean dcmpsrs & organic N	Ocean humus N	OceanhumusN
N	Oceans	N	Deep ocean dcmpsrs & other organic N	Ocean humus N	OceanhumusN
N	Oceans	N	Marine sediments organic N	Marine sediments N	OceanhumusN
N	Oceans	NH_4^+	Marine sediments ammonium	Marine sediments N	OceannecN

Table E.5 Concordance Mapping Environment Commodity Stocks between Chapters (Cont.)

Cycle	Sphere	Chemical Formula	Stock Name - Chapters 4 and 5 (Within Env. & between Env. & Economy)	Stock Name - Chapter 6 (Ecotime Analysis)	Stock Name - Chapter 8 (DGBCM)
P	Atmosphere	PO_4^{3-}	Phosphate aerosols	Phosphate aerosols	N/A
P	Terrestrial biosphere	$C_{790}N_{7.6}S_{3.1}P_1$	Vegetation P	Vegetation P	VegezoomasP
P	Terrestrial biosphere	$C_{115.8}N_{14.5}S_{0.2}P_1$	Zoomas P	Zoomass P	VegezoomasP
P	Terrestrial biosphere	P	Litter/detritus P	Litter/detritus P	DetritusP
P	Terrestrial biosphere	P	Other soil organic matter P	Soil P	SoilP
P	Terrestrial biosphere	PO_4^{3-}	Soil inorganic P	Soil P	SoilP
P	Terrestrial biosphere	P	Landfilled solid waste P	N/A	N/A
P	Lithosphere	P	Kerogen P	Kerogen P	LithosphereP
P	Lithosphere	$C_{131}N_2S_1P_{0.2}$	Coal P	Coal P	CoalP
P	Lithosphere	P	Other lithosphere P	Other lithosphere P	LithosphereP
P	Oceans	HPO_4^{3-}	Ocean inorganic P	Ocean inorganic P	OceannecP
P	Oceans	$C_{108}N_{15.5}S_{1.3}P_1$	Marine photoautotrophs P	Marine photoautotrophs P	OceanpandcP
P	Oceans	$C_{103}N_{16.5}S_{1.3}P_1$	Marine consumers P	Marine consumers P	OceanpandcP
P	Oceans	P	Surface ocean dcmpsrs & organic P	Ocean humus P	OceanhumusP
P	Oceans	P	Deep ocean dcmpsrs & other organic P	Ocean humus P	OceanhumusP
P	Oceans	P	Marine sediments organic P	Marine sediments P	OceanhumusP
P	Oceans	PO_4^{3-}	Marine sediments inorganic P	Marine sediments P	OceannecP
S	Atmosphere	SO_4^{2-}	Atmospheric sulphate	Atmospheric sulphate	AtmosnecS
S	Atmosphere	SO_2	S dioxide	S dioxide	AtmosnecS
S	Atmosphere	CS_2	C disulfide	C disulfide	AtmosnecS
S	Atmosphere	OCS	Carbonyl sulfide S	Carbonyl sulfide C	AtmosnecS
S	Atmosphere	H_2S	Hydrogen sulfide	Hydrogen sulfide	AtmosnecS
S	Atmosphere	$(CH_3)_2S$	Dimethyl sulfide S	Dimethyl sulfide S	AtmosnecS
S	Terrestrial biosphere	$C_{790}N_{7.6}S_{3.1}P_1$	Vegetation S	Vegetation S	VegezoomasS
S	Terrestrial biosphere	$C_{115.8}N_{14.5}S_{0.2}P_1$	Zoomas S	Zoomass S	VegezoomasS
S	Terrestrial biosphere	S	Litter/detritus S	Litter/detritus S	DetritusS
S	Terrestrial biosphere	S	Soil organic S	Soil S	SoilS
S	Terrestrial biosphere	SO_4^{2-}	Soil inorganic S	Soil S	SoilS
S	Terrestrial biosphere	S	Landfilled solid waste S	N/A	N/A
S	Lithosphere	S	Kerogen S	Kerogen S	LithosphereS
S	Lithosphere	$C_{131}N_2S_1P_{0.2}$	Coal S	Coal S	CoalS
S	Lithosphere	$C_{129}N_1S_1$	Petroleum S	Petroleum S	PetroleumS
S	Lithosphere	S	Other lithosphere S	Other lithosphere S	LithosphereS
S	Oceans	SO_4^{2-}	Ocean inorganic S	Ocean inorganic S	OceannecS
S	Oceans	$C_{108}N_{15.5}S_{1.3}P_1$	Marine photoautotrophs S	Marine photoautotrophs S	OceanpandcS
S	Oceans	$C_{103}N_{16.5}S_{1.3}P_1$	Marine consumers S	Marine consumers S	OceanpandcS
S	Oceans	S	Surface ocean dcmpsrs & organic S	Ocean humus S	OceanhumusS
S	Oceans	S	Deep ocean dcmpsrs & other organic S	Ocean humus S	OceanhumusS
S	Oceans	S	Marine sediments organic S	Marine sediments S	OceanhumusS
S	Oceans	S	Marine sediments inorganic S	Marine sediments S	OceannecS

Table E.6 Reporting Environmental Commodity Stock Concordance

Chapter Reporting Environmental Commodity Stock	Stock Name - Chapters 4 and 5 (Within Env. & between Env. & Economy)
Carbon dioxide	C dioxide
Atmos C	Methane, C monoxide, Volatile organic C, Carbonyl sulfide C, C disulfide, Dimethyl sulfide C
Vegetation C	Vegetation C
Other C	Zoomas C, Landfilled solid waste C, Kerogen C, Carbonate minerals, Other lithosphere C, Other ocean inorganic C, Marine photoautotrophs C, Marine consumers C, Surface ocean dcmpsrs & organic C, Surface ocean calcium carbonates, Deep ocean dcmpsrs & other organic C, Deep ocean calcium carbonates, Marine sediments organic C, Marine sediments calcium carbonates
Soil C	Litter/detritus C, Other soil organic matter C, Soil inorganic C
Coal C	Coal C
Petroleum C	Petroleum C
Gas C	Natural gas C
Dinitrogen	Dinitrogen
Atmos N	N oxides, Nitrous oxide, Ammonia/ammonium
Vegetation N	Vegetation N
Other N	Zoomas N, Landfilled solid waste N, Kerogen N, Other lithosphere N, Ocean inorganic N, Marine photoautotrophs N, Marine consumers N, Surface ocean dcmpsrs & organic N, Deep ocean dcmpsrs & other organic N, Marine sediments organic N, Marine sediments ammonium
Soil N	Litter/detritus N, Other soil organic matter N, Soil inorganic N
Coal N	Coal N
Petroleum N	Petroleum N
Other P	Phosphate aerosols, Zoomas P, Landfilled solid waste P, Kerogen P, Other lithosphere P, Ocean inorganic P, Marine photoautotrophs P, Marine consumers P, Surface ocean dcmpsrs & organic P, Deep ocean dcmpsrs & other organic P, Marine sediments organic P, Marine sediments inorganic P
Vegetation P	Vegetation P
Soil P	Litter/detritus P, Other soil organic matter P, Soil inorganic P
Coal P	Coal P
Atmos S	Atmospheric sulphate, S dioxide, C disulfide, Carbonyl sulfide S, Hydrogen sulfide, Dimethyl sulfide S
Vegetation S	Vegetation S
Other S	Zoomas S, Landfilled solid waste S, Kerogen S, Other lithosphere S, Ocean inorganic S, Marine photoautotrophs S, Marine consumers S, Surface ocean dcmpsrs & organic S, Deep ocean dcmpsrs & other organic S, Marine sediments organic S, Marine sediments inorganic S
Soil S	Litter/detritus S, Soil organic S, Soil inorganic S
Coal S	Coal S
Petroleum S	Petroleum S

Appendix F

Additional Equations for the Dynamic General Equilibrium-*Seeking* Model

F.1 Variable Definitions

Stocks

$Pcfact_j$	Composite factor price for industry j
$Pfact_{h,j}$	Factor h price for industry j
$Pskill_p$	Skill p price
$Prodf_h$	Productivity variable for factor h

Flows

$pcfactadjust_j$	Adjustment to composite factor price for industry j
$changepfact_{h,j}$	Increase in factor h price for industry j
$changepskill_p$	Increase in skill p price

Converters (Excluding Constants)

$actualpcfact_j$	Calculated price for composite factors for industry j
$desiredpfact_{h,j}$	Desired $Pfact_{h,j}$ in response to factor h availability
$desiredpskill_p$	Desired $Pskill_p$ in response to skill p availability
$effectpfact_{h,j}$	Price change effect for factor h in industry j
$effectpskill_p$	Price change effect for skill p
$factorsd_{h,j}$	Demand for factor h by industry j
$factorratio_{h,j}$	Ratio of factor h supplied to demanded for industry j
$factorss_{h,j}$	Supply of factor h to industry j
$skillratio_p$	Ratio of supplied skill p to desired skill p

Constants

$CDPFACT_{h,j}$	Change delay for factor h price for industry j
$CDPSKILL_p$	Change delay for skill p price

$LOOKUPPFACT_{h,j}$	Lookup function determining the scalar to apply to $Pfact_{h,j}$ in response to the relative supply and demand for factor h within industry j
$LOOKUPPSKILL_p$	Lookup function determining the scalar to apply to $Pskill_p$ in response to the relative supply and demand for skill p
$RPRODF_h$	Rate of productivity growth for factor h
$TIMESTEP$	Iteration time step applied in the model

F.2 Equations

$$Pfact_{h,j}(t+dt) = Pfact_{h,j}(t) + changepfact_{h,j} \times dt$$
where:
$$Pfact_{h,j}(0) = 1 \quad \text{(F.1)}$$

$$changepfact_{h,j} = \frac{desiredpfact_{h,j} - Pfact_{h,j}}{CDPFACT_{h,j}} \quad \text{(F.2)}$$

$$desiredpfact_{h,j} = Pfact_{h,j} \times effectpfact_{h,j} \quad \text{(F.3)}$$

$$effectpfact_{h,j} = LOOKUPPFACT_{h,j}\left(factorratio_{h,j}\right) \quad \text{(F.4)}$$

$$factorratio_{h,j} = \frac{factorss_{h,j}}{factorsd_{h,j}} \quad \text{(F.5)}$$

$$Pcfact_j(t+dt) = Pcfact_j(t) + pcfactadjust_j \times dt$$
where:
$$Pcfact_j(0) = 1 \quad \text{(F.6)}$$

$$pcfactadjust_j = \left(actualpcfact_j - Pcfact_j\right) \times \left(\frac{1}{TIMESTEP}\right) \quad \text{(F.7)}$$

$$actualpcfact_j = \frac{\sum_h \left(factorsd_{h,j} \times Pfact_{h,j}\right)}{qcomfactd_j} \quad \text{(F.8)}$$

$$qcomfact_j = SCALEP_j \times \left(\sum_h \left(SHAREP_{h,j} \times factorsd_{h,j}^{\,factsubstp_j}\right)\right)^{\frac{1}{factsubstp_j}} \quad \text{(F.9)}$$

$$Pskill_p(t+dt) = Pskill_p(t) + changepskill \times dt$$
where:
$$Pskill_p(0) = 1 \quad \text{(F.10)}$$

$$changepskill_p = \frac{desiredpskill_p - Pskill_p}{CDPSKILL_p} \quad \text{(F.11)}$$

$$desiredpskill_p = Pskill_p \times effectpskill_p \quad \text{(F.12)}$$

$$effectpskill_p = LOOKUPPSKILL_p\left(skillratio_p\right) \quad \text{(F.13)}$$

$$skillratio_p = \frac{skills_p}{skilld_p} \quad \text{(F.14)}$$

Appendix G

Further Specification of the Ecocycle Model

G.1 Energy Module

G.1.1 Diagrammatic Representation

The Vensim DSS® influence diagram for the Ecocycle energy module is provided in Figure G.1

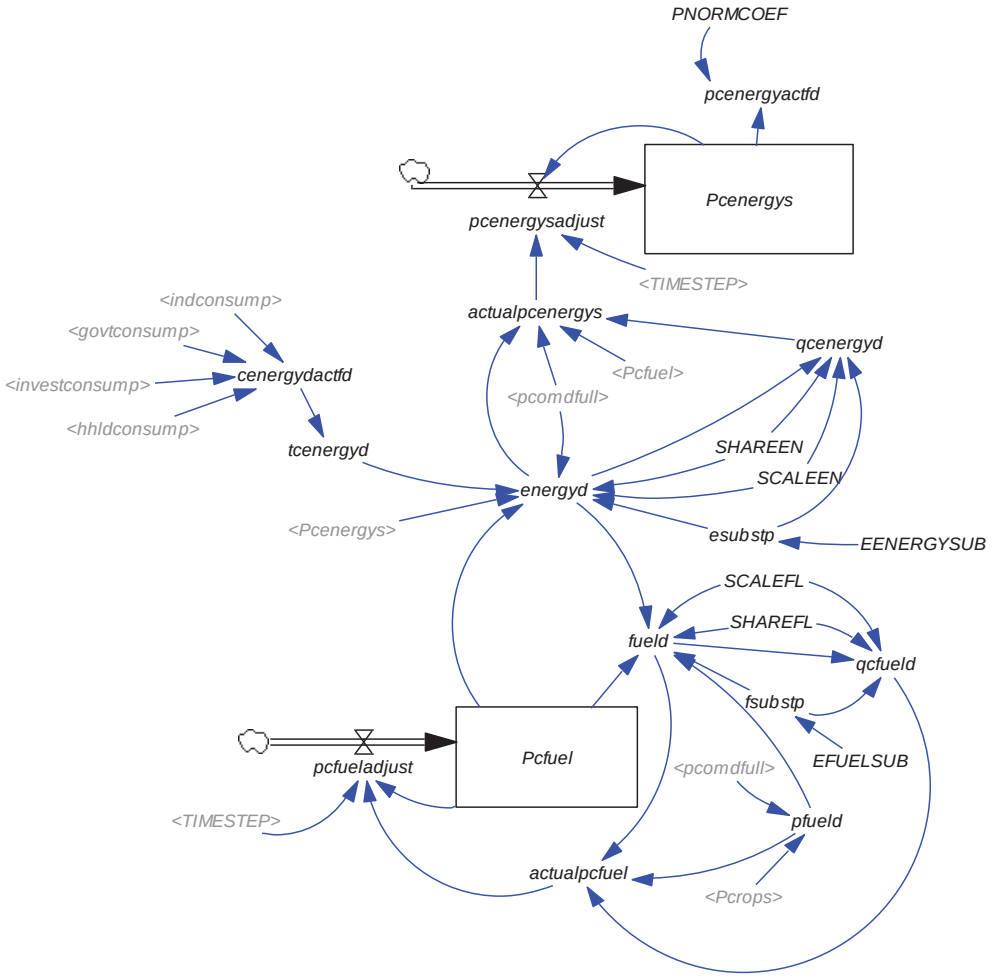

Figure G.1 Energy Module Influence Diagram

G.1.2 Variable Definitions

Stocks

Pcenergys	Demand price for composite energy
Pcfuel	Demand price for composite fuels

Flows

pcenergysadjust	Adjustment to composite energy price
pcfueladjust	Adjustment to composite fuel price

Converters (Excluding Constants)

actualpcenergys	Calculated price for composite energy based on the weighted average price of inputs
actualpcfuel	Calculated price for composite fuels based on the weighted average price of inputs
$cenergydactfd_{\gamma}$	Composite energy demands by sector γ
ctransp	Transformation parameter within the CET function for crop supply
$energyd_g$	Demand for energy g ($g \in \{\text{ElectEF}, \text{FuelsEF}\}$)
esubstp	Input substitution parameter between electricity and composite fuels
fsubstp	Input substation parameter between fuels
$fueld_f$	Demand for fuel type f ($f \in \{\text{CropFL}, \text{CoalFL}, \text{OilfFL}, \text{GasfFL}, \text{PetrFL}\}$)
$pcenergyactfd_{\gamma}$	Demand price for composite energy for sector γ
$pfueld_f$	Demand price for fuel f
qcenergyd	Quantity of composite energy demanded, as derived from the calculated electricity and composite fuel demands
qcfueld	Quantity of composite fuels demanded, as derived from the calculated demands for individual fuels
tcenergyd	Sum of all composite energy demands

Constants

SCALEEN	Scale parameter within the CES function for composite energy
SCALEFL	Scale parameter within the CES function for composite fuels

$SHAREEN_g$	Share parameter for energy g within the CES function for composite energy
$SHAREFL_f$	Share parameter for fuel f within the CES function for composite fuels
$TIMESTEP$	Time between model iterations
$EENERGYSUB$	Elasticity of substitution between electricity and composite fuels
$EFUELSUB$	Elasticity of substitution between fuels

G.1.3 Equations

$$energyd_{\text{ElectEF}} = \left(\frac{SCALEEN^{\,esubstp} \times SHAREEN_{\text{ElectEF}} \times Pcenergys}{pcomdfull_{\text{ElectEF}}} \right)^{\frac{1}{1-esubstp}} \times tcenergyd$$
$$energyd_{\text{FuelsEF}} = \left(\frac{SCALEEN^{\,esubstp} \times SHAREEN_{\text{FuelsEF}} \times Pcenergys}{Pcfuel} \right)^{\frac{1}{1-esubstp}} \times tcenergyd \quad \text{(G.1)}$$

$$esubstp = \frac{ENERGYSUB - 1}{ENERGYSUB} \quad \text{(G.2)}$$

$$tcenergyd = \sum_{\gamma} cenergydactfd_{\gamma} \quad \text{(G.3)}$$

$$\gamma \in \{\text{ind1, ind2, ..., ind}\pi\} \Rightarrow cenergydactfd_{\gamma} = indconsump_{\text{EnergSC},\gamma}$$
$$\gamma = households \Rightarrow cenergydactfd_{\gamma} = hhldconsump_{\text{EnergSC}}$$
$$\gamma = government \Rightarrow cenergydactfd_{\gamma} = govtconsump_{\text{EnergSC}} \quad \text{(G.4)}$$
$$\gamma = investment \Rightarrow cenergydactfd_{\gamma} = investconsump_{\text{EnergSC}}$$

$$Pcenergys(t + dt) = Pcenergys(t) + pcenergysadjust \times dt$$
where: (G.5)
$Pcfact_j(0) = 1 +$ average production tax rate on all energy commodities

$$pcenergysadjust = (actualpcenergys - Pcenergys) \times \left(\frac{1}{TIMESTEP} \right) \quad \text{(G.6)}$$

$$actualpcenergys = \frac{energyd_{electEF} \times pcomdfull_{electFC} + energyd_{fuelsEF} \times Pcfuel}{qcenergyd} \quad \text{(G.7)}$$

$$qcenergyd = SCALEEN \times \left(\sum_{g} \left(SHAREEN_g \times energyd_g^{\,esubstp} \right) \right)^{\frac{1}{esubstp}} \quad \text{(G.8)}$$

$$Pcfuel(t + dt) = Pcfuel(t) + pcfueladjust \times dt$$
where: (G.9)
$Pcfuel(0) = 1 +$ average production tax rate on all fuel commodities

$$pcfueladjust = (actualpcfuel - Pcfuel) \times \left(\frac{1}{TIMESTEP} \right) \quad \text{(G.10)}$$

$$actualpcfuel = \frac{\sum_{f}\left(fueld_f \times pfueld_f \right)}{qcfueld} \tag{G.11}$$

$$qcfueld = SCALEFL \times \left(\sum_{f} \left(SHAREFL_f \times fueld_f{}^{fsubstp} \right) \right)^{\frac{1}{fsubstp}} \tag{G.12}$$

$$fueld = \left(\frac{SCALEFL^{fsubstp} \times SHAREFL_f \times Pcfuel}{pfueld_f} \right)^{\frac{1}{1-fsubstp}} \times energyd_{\text{FuelsEF}} \tag{G.13}$$

$$fsubstp = \frac{EFUELSUB - 1}{EFUELSUB} \tag{G.14}$$

$$\begin{aligned} f \neq \text{CropFL} &\Rightarrow pfueld_f = pcomdfull_f \\ f = \text{CropFL} &\Rightarrow pfueld_f = Pcrops_{\text{CropEN}} \end{aligned} \tag{G.15}$$

$$pcenergyactfd_\gamma = Pcenergys_\gamma \times PNORMCOEF_\gamma \tag{G.16}$$

G.2 Commodities Module

This section describes only the modifications to the original DGES model included within the Ecocycle model. Reference should be made to Section 7.3.1 for all remaining variable definitions and equations.

G.2.1 Diagrammatic Representation

The Vensim DSS® influence diagram for the Ecocycle commodities module is provided in Figure G.2.

G.2.2 Variable Definitions

Stocks

$Pcoms_i$	Supply price for commodity i
$Pcrops_c$	Demand price of crop type c ($c \in \{\text{CropEN}, \text{CropFF}\}$)
$Crops_c$	Inventory of crop c

Flows

$cropsupply_c$	Supply of crop c
$cropuse_c$	Total use of crop c

$changepcrops_c$	Increase in crop c demand price

Converters (Excluding Constants)

$cropsratio_c$	Ratio of supplied crop c to demanded crop c
$desiredpcrops_c$	Desired $Pcrop_c$ in response to crop availability
$effectpcrops_c$	Price change effect for crop c
$interinputshare_{i*,j}$	Share of intermediate inputs to industry j comprised of commodity i*
$pcomdfull_i$	Demand price for commodity i
$pcomdshortact_{j,i*}$	Demand price for commodity i* faced by industry j
$pcomdshortactfd_{\gamma,i*}$	Demand price for commodity i* faced by sector γ
$pefficiencyeffect_{i*,j}$	Efficiency scalar for commodity i* use within industry j
$pintgood_j$	Price for intermediate goods within industry j
$productionc_i$	Production of commodity i
$relativepriceinputs_{i*,j}$	Ratio of commodity i* price for industry j relative to the weighted average price of all intermediate goods for that industry
$taxprodc_i$	Production tax rate for commodity i
use_i	Total use of commodity i

Constants

$AX_{i*,j}$	Intermediate input coefficient for commodity i* within industry j
$BASEINPUTSH_{j,\lambda}$	The value of $ficoeff_{j,\lambda}$ at the base year
$BASERELATIVEP_{i*,j}$	Price of commodity i relative to the weighted intermediate goods price for industry j at the base year
$CDPCROPS_c$	Change delay for crop c price
$LOOKUPPCROPS_c$	Lookup function determining the scalar to apply to $Pcrop_c$, given relative supply and demand for that crop
$ECROPTRANS$	The elasticity of supply between biofuel crops and food and fibre crops
$EFFLOOKUP_j$	Lookup function that determines the price efficiency effect for a commodity input within industry j given the relative price of that commodity
$SCALECR$	Scale parameter within the CET function for crop supply
$SHARECR_c$	Share parameter for crop type c within the CET function for crop supply

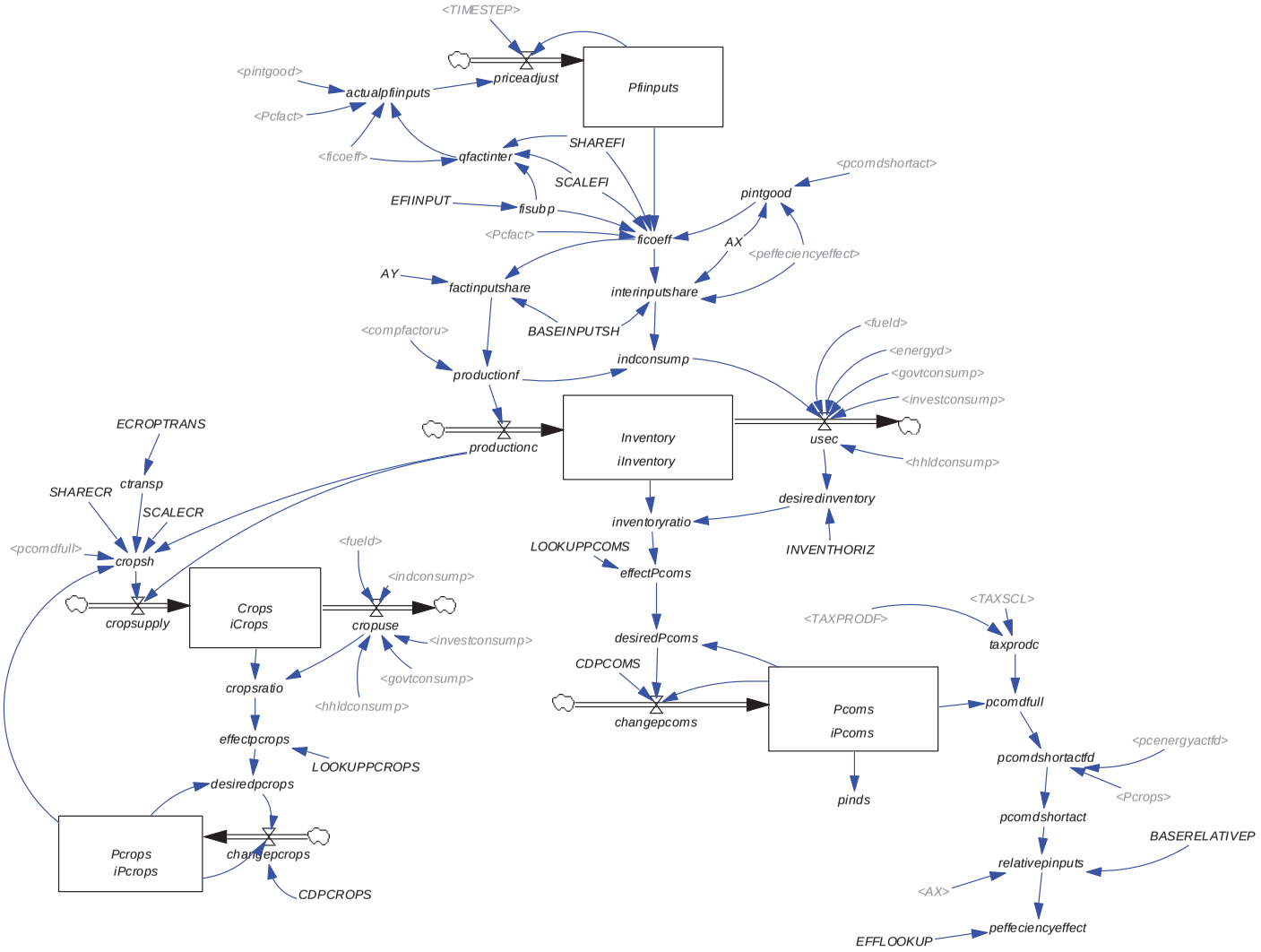

Figure G.2 Commodities Module Influence Diagram

G.2.3 Equations

$$cropsh_c = \left(\frac{SCALECR^{ctransp} \times SHARECR_c \times pcomdfull_{\text{CropsFC}}}{Pcrops_c} \right)^{\frac{1}{ctransp}} \times productionc_{\text{CropsFC}} \quad \text{(G.17)}$$

$$cropssupply_c = \frac{cropsh_c}{\sum_c cropsh_c} \times productionc_{\text{CropsFC}} \quad \text{(G.18)}$$

$$ctransp = \frac{ECROPTRANS + 1}{ECROPTRANS} \quad \text{(G.19)}$$

$$\begin{aligned} cropuse_{\text{CropEN}} &= fueld_{\text{CropFL}} \\ cropuse_{\text{CropFF}} &= \sum_j indconsump_{\text{CropsSC},j} + hhldconsump_{\text{CropsSC},j} + govtconsump_{\text{CropsSC},j} \\ &\quad + investconsump_{\text{CropsSC},j} \end{aligned} \quad \text{(G.20)}$$

$$pcomdfull_i = Pcoms_i \times (1 + taxprodc_i) \quad \text{(G.21)}$$

$$\begin{aligned} &i^* \notin \{\text{CropsSC,EnergSC}\} \Rightarrow pcomdshortactfd_{\gamma,i^*} = pcomdfull_i \quad \forall i^* = i \\ &i^* = \text{CropSC} \Rightarrow pcomdshortactfd_{\gamma,i^*} = Pcrops_{\text{CropFF}} \\ &i^* = \text{EnergSC} \Rightarrow pcomdshortactfd_{\gamma,i^*} = pcenergyd_\gamma \end{aligned} \quad \text{(G.22)}$$

$$pcomdshortact_{j,i^*} = pcomdshortactfd_{\gamma,i^*} \quad \forall \gamma = j \quad \text{(G.23)}$$

$$Pcrops_c(t + dt) = Pcrops_c(t) + changepcrops_c \times dt$$
where: (G.24)
$$Pcrops_c(0) = 1 + taxprodc_{\text{CropsFC}}$$

$$changepcrops_c = \frac{desiredpcrops_c - Pcrops_c}{CDPCROPS_c} \quad \text{(G.25)}$$

$$desiredpcrops = Pcrops_c \times effectpcrops_c \quad \text{(G.26)}$$

$$effectpcrops_c = LOOKUPPCROPS_c(cropsratio_c) \quad \text{(G.27)}$$

$$cropsratio_c = \frac{Crops_c}{cropuse_c} \quad \text{(G.28)}$$

$$Crops_c(t + dt) = Crops_c(t) + (cropsupply_c - cropuse_c) \times dt$$
where: (G.29)
$Crops_c(0) = cropuse_c$ at the base year

$$
\begin{aligned}
&i = \text{ElectFC} \Rightarrow use_i = energyd_{\text{ElectEF}} \\
&i \in \{\text{CoalfFL,OilffFL,GasffFL,PetrlFL}\} \Rightarrow use_i = fueld_f \\
&i = \text{CropsFL} \Rightarrow use_i = govtconsump_{\text{CropSC}} + investconsump_{\text{CropSC}} + hhldconsump_{\text{CropSC}} \\
&\qquad + \sum_j indconsump_{\text{CropSC},j} + fueld_{\text{CropFL}} \qquad \text{(G.30)} \\
&i \notin \begin{Bmatrix} \text{ElectFC,CoalfFL,OilffFL,} \\ \text{GasffFL,PetrlFL,CropsFC} \end{Bmatrix} \Rightarrow use_i = govtconsump_{i^*} + investconsump_{i^*} + hhldconsump_{i^*} \\
&\qquad + \sum_j indconsump_{i^*,j} \;\; \forall i = i^*
\end{aligned}
$$

$$
relativepinputs_{i^*,j} = \frac{pcomdshortact_{i^*,j} \times \sum_{i^*} AX_{i^*,j}}{\sum_{i^*} \left(pcomdshortact_{i^*,j} \times AX_{i^*,j} \right) \times BASERELATIVEP_{i^*,j}} \qquad \text{(G.31)}
$$

$$
pefficiencyeffect_{i^*,j} = EFFLOOKUP_j \left(relativepinputs_{i^*,j} \right) \qquad \text{(G.32)}
$$

$$
pintgood_j = \frac{\sum_{i^*} AX_{i^*,j} \times pefficiencyeffect_{i^*,j} \times pcomdshort_{i^*,j}}{\sum_{i^*} AX_{i^*,j}} \qquad \text{(G.33)}
$$

$$
interinputshare_{i^*,j} = \frac{AX_{i^*,j} \times pefficiencyeffect_{i^*,j} \times ficoeff_{j,\text{InterI}}}{BASEINPUTSH_{j,\text{InterI}}} \qquad \text{(G.34)}
$$

G.3 Capital Module

G.3.1 Diagrammatic Representation

The Vensim DSS® influence diagram for the Ecocycle capital module is provided in Figure G.3.

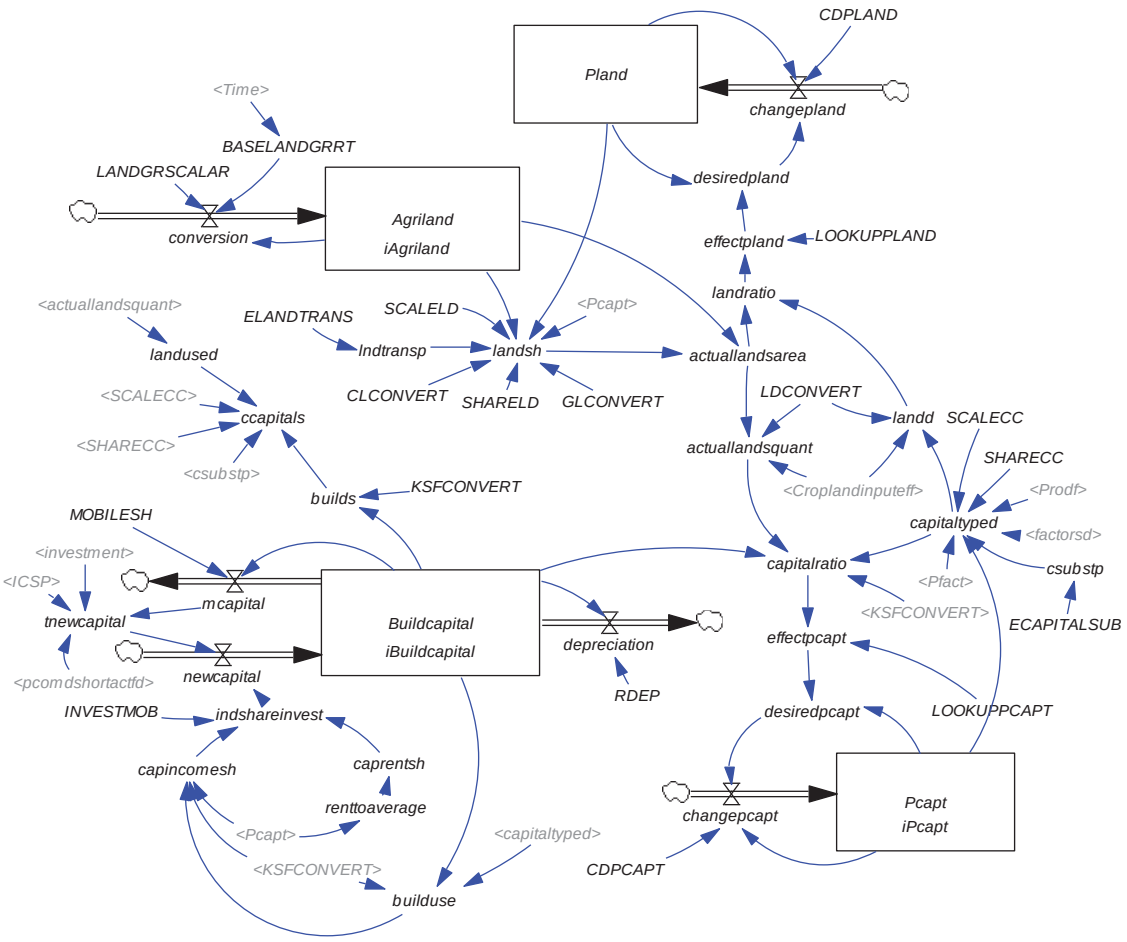

Figure G.3 Capital Module Influence Diagram

G.3.2 Variable Definitions

Stocks

Agriland	Area of land available for agriculture
$Buildcapital_j$	Stock of non-land capital held by industry j
Pland	Average land price
$Pcapt_{k,j}$	Capital k price for industry j

Flows

$changepcapt_{k,j}$	Increase in the price of capital k for industry j
$changepland$	Increase in the average land price
$conversion$	Net conversion of land for agriculture
$depreciation_j$	Depreciation of non-land capital held by industry j
$mcapital_j$	Capital held by industry j that is available for redistribution to other industries
$newcapital_j$	Additions of non-land capital within industry j

Converters (Excluding Constants)

$actuallandsarea_l$	The area of land of type l supplied
$actuallandsquant_l$	The quantity of land l factor supplied
$builds_j$	Endowment of other capital for industry j
$builduse_j$	Use of non-land capital by industry j
$capincomesh_j$	Share of total non-land capital income derived from industry j
$capitalratio_{k,j}$	Ratio of supply to demand for capital k and industry j
$capitaltyped_{k,j}$	The quantity of capital k demanded by industry j
$caprentsh$	Share of new or redistributed non-land capital allocated to industry j based on the relative price of non-land capital within that industry
$ccapitals_j$	Supply of composite capital to industry j
$csubstp_j$	Capital input substitution parameter for industry j
$desiredpcapt_{k,j}$	Desired $Pcapt_{k,j}$ in response to supply and demand
$desiredpland$	Desired $Pland$ in response to supply and demand
$effectpcapt_{k,j}$	Price change effect for capital k and industry j
$effectpland$	Price change effect for land
$indshareinvest_j$	Share of new or redistributed non-land capital allocated to industry j
$landd$	Total area of agricultural land demand
$landratio$	Ratio of land supply to land demand
$landsh_l$	Stock of land allocated to land type l based on the CET function
$landtransp$	Land supply substitution parameter
$landused_j$	The quantity of land supplied to industry j
$renttoaverage_j$	Ratio of the non-land capital price for industry j to the average non-land capital price
$tnewcapital$	Total new capital available for investment within industries

Constants

$CDPCAPT_{k,j}$	Change delay for the price of capital for industry j
$CDPLAND$	Change delay for the average price of land
$CLCONVERT$	Scalar determining the price of cropland relative to the average land price
$ECAPITALSUB_j$	The elasticity of input substitution between land and other capital within industry j
$ELANDTRANS$	The elasticity of supply between crop land and grazing land
$GLCONVERT$	Scalar determining the price of grazing land relative to the average land price
$INVESTMOB$	Share of capital income that is available for investment within any industry
$KSFCONVERT_j$	Scalar to convert a stock of Buildcapital held by industry j into a monetary unit of the annual quantity of the factor supplied
$LANDGRRT$	Net rate of growth in agricultural land
$LDCONVERT_j$	Scalar to convert an area of land used by industry j into a monetary unit of the annual quantity of the factor supplied
$LOOKUPPCAPT_{k,j}$	Lookup function determining the scalar to apply to $Pcapt_{k,j}$ in response to supply and demand for that factor
$LOOKUPPLAND$	Lookup function determining the scalar to apply to $Pland$ in response to supply and demand for agricultural land
$MOBILESH_j$	Share of capital held by industry j that is potentially mobile between industries
$RDEP_j$	Rate of capital depreciation within industry j
$SCALECC_j$	Scale parameter for industry j within the CES function for composite capital
$SCALELD$	Scale parameter within the CET function for land supply
$SHARECC_{j,k}$	Share parameter for industry j and capital k within the CES function for composite capital
$SHARELD_l$	Share parameter for land l within the CET function for land supply

G.3.3 Equations

$$Pland\left(t+dt\right)=Pland\left(t\right)+changepland\times dt$$
where: (G.35)
$$Pland\left(0\right)=1$$

$$changepland=\frac{desiredpland-Pland}{CDPLAND} \quad \text{(G.36)}$$

$$desiredpland=Pland\times effectpland \quad \text{(G.37)}$$

$$effectpland=LOOKUPPLAND\left(landratio\right) \quad \text{(G.38)}$$

$$landratio=\frac{\sum_{l} actuallandsarea_{l}}{landd} \quad \text{(G.39)}$$

$$Pcapt_{k,j}\left(t+dt\right)=Pcapt_{k,j}\left(t\right)+changepcapt_{k,j}\times dt$$
where: (G.40)
$$Pcapt_{k,j}\left(0\right)=1$$

$$changepcapt_{k,j}=\frac{desiredpcapt_{k,j}-Pcapt_{k,j}}{CDPCAPT} \quad \text{(G.41)}$$

$$desiredpcapt_{k,j}=Pcapt_{k,j}\times effectpcapt_{k,j} \quad \text{(G.42)}$$

$$effectpcapt_{k,j}=LOOKUPPCAPT_{k,j}\left(capitalratio_{k,j}\right) \quad \text{(G.43)}$$

$$capitalratio_{\text{BuilC},j}=\frac{Buildcapital_{j}\times KSFCONVERT_{j}}{capitaltyped_{\text{BuilC},j}}$$
$$j\notin\left\{\text{CropsA, AnimsA}\right\}\Rightarrow capitalratio_{\text{LandC},j}=1$$
$$j=\text{CropsA}\Rightarrow capitalratio_{\text{LandC},j}=\frac{actuallandsquant_{\text{CropL}}}{capitaltyped_{\text{LandC},j}} \quad \text{(G.44)}$$
$$j=\text{AnimsA}\Rightarrow capitalratio_{\text{LandC},j}=\frac{actuallandsquant_{\text{GrazL}}}{capitaltyped_{\text{LandC},j}}$$

$$capitaltyped_{k,j}=\left(\frac{SCALECC_{j}^{\,csubstp_{j}}SHARECC_{k,j}\times Pfact_{cap,j}}{Pcapt_{k,j}}\right)^{\frac{1}{1-csubstp_{j}}}\times\frac{factorsd_{cap,j}}{Prodf_{cap}} \quad \text{(G.45)}$$

$$csubstp_{j}=\frac{ECAPITALSUB_{j}-1}{ECAPITALSUB_{j}} \quad \text{(G.46)}$$

$$landd=\frac{capitaltyped_{\text{LandC,CropsA}}}{LDCONVERT_{\text{CropsA}}\times Croplandinputeff}+\frac{capitaltyped_{\text{LandC,AnimsA}}}{LDCONVERT_{\text{AnimsA}}} \quad \text{(G.47)}$$

$$actuallandsquant_{\text{CropL}}=actuallandsarea_{\text{CropL}}\times LDCONVERT_{\text{CropsA}}\times Croplandinputeff$$
$$actuallandsquant_{\text{GrazL}}=actuallandsarea_{\text{GrazL}}\times LDCONVERT_{\text{AnimsA}} \quad \text{(G.48)}$$

$$landsh_{\text{CropL}} = \left(\frac{SCALELD^{lndtransp} \times SHARELD_{\text{CropL}} \times Pland}{Pcapt_{\text{LandC,CropsA}} \times CLCONVERT} \right)^{\frac{1}{1-lndtransp}} \times Agriland$$

$$landsh_{\text{GrazL}} = \left(\frac{SCALELD^{lndtransp} \times SHARELD_{\text{GrazL}} \times Pland}{Pcapt_{\text{LandC,AnimsA}} \times GLCONVERT} \right)^{\frac{1}{1-lndtransp}} \times Agriland \quad \text{(G.49)}$$

$$actuallandsarea = \frac{landsh_l}{\sum_l landsh_l} \times Agriland \quad \text{(G.50)}$$

$$builds_j = Buildcapital_j \times KSFCONVERT_j \quad \text{(G.51)}$$

$$j \notin \{\text{CropsA, AnimsA}\} \Rightarrow ccapitals_j = builds_j$$

$$j \in \{\text{CropsA, AnimsA}\} \Rightarrow ccapitals_j = SCALECC_j \times \left(\begin{array}{l} SHARECC_{\text{BuilC},j} \times builds_j^{\,csubstp_j} + \\ \text{SHARECC}_{\text{LandC},j} \times landused_j^{\,csubstp_j} \end{array} \right)^{\frac{1}{csubstp_j}} \quad \text{(G.52)}$$

$$\begin{array}{l} j \notin \{\text{CropsA, AnimsA}\} \Rightarrow landused_j = 0 \\ j = \text{CropsA} \Rightarrow landused_j = actuallandsquant_{\text{CropL}} \\ j = \text{AnimsA} \Rightarrow landused_j = actuallandsquant_{\text{GrazL}} \end{array} \quad \text{(G.53)}$$

$$Agriland(t+1) = Agriland(t) + conversion \times d\text{t}$$

where (G.54)

$Agriland(t) =$ area of crop and grazing land at t=0

$$conversion = Agriland \times LANDGRRT \quad \text{(G.55)}$$

$$Buildcapital_j(t+dt) = Buildcapital_j(t) + (newcapital_j - depreciation_j - mcapital_j) \times dt$$

where: (G.56)

$Capital_j(0) =$ size of non-land capital stock held by industry j at the base year

$$depreciation_j = Buildcapital_j \times RDEP_j \quad \text{(G.57)}$$

$$mcapital_j = Buildcapital_j \times MOBILESH_j \quad \text{(G.58)}$$

$$tnewcapital_j = investment \times \sum_{i^*} \left(\frac{ICSP_{i^*}}{pcomdshortactfd_{i^*}} \right) + \sum_j mcapital_j \quad \text{(G.59)}$$

$$newcapital_j = tnewcapital \times indshareinvest_j \quad \text{(G.60)}$$

$$capincomesh_j = \frac{builduse_j \times KSFCONVERT_j \times Pcapt_{\text{BuildC},j}}{\sum_j (builduse_j \times KSFCONVERT_j \times Pcapt_{\text{BuildC},j})} \quad \text{(G.61)}$$

$$indshareinvest_j = capincomesh_j \times (1 - INVESTMOB) + caprentsh_j \times INVESTMOB \quad \text{(G.62)}$$

$$caprentsh_j = \frac{renttoaverage_j}{\sum_j renttoaverage_j} \quad \text{(G.63)}$$

$$renttoaverage_j = \frac{Pcapt_{\text{BuilC},j}}{\sum_j Pcapt_{\text{BuilC},j}} \tag{G.64}$$

$$builduse_j = \min\left(Buildcapital_j \times KSFCONVERT_j, capitaltyped_{\text{BuildC},j}\right) \tag{G.65}$$

G.4 Factors Module

This section describes only the modifications to the original DGES model included within the Ecocycle model. Reference should be made to Section 7.3.1 for all remaining variable definitions and equations.

G.4.1 Diagrammatic Representation

The Vensim DSS® influence diagram for the Ecocycle factors module is provided in Figure G.4.

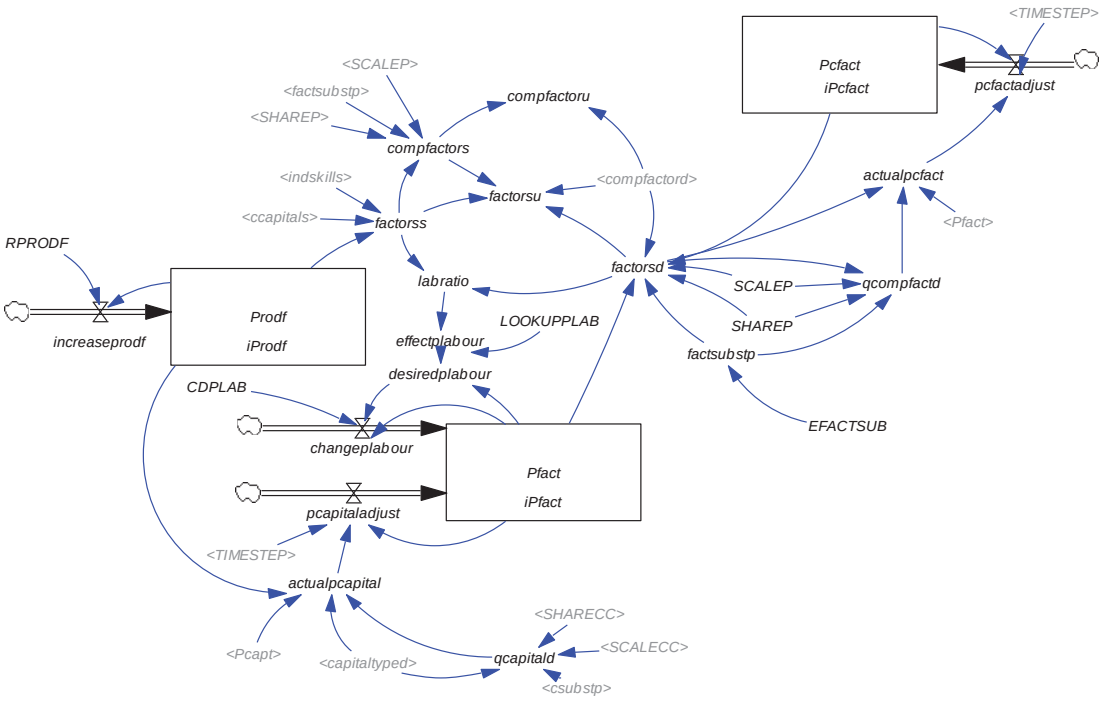

Figure G.4 Factors Module Influence Diagram

G.4.2 Variable Definitions

Stocks

$Pcapt_{k,j}$ Price for capital type k within industry *j*

$Pfact_{h,j}$	Factor h price for industry j
$Prodf_h$	Productivity of factor h

Flows

changeplabour	Increase in labour price
$pcapitaladjust_j$	Adjustment to composite capital price for industry j

Converters (Excluding Constants)

$actualpcapital_j$	Calculated price for composite capital within industry j
$capitaltyped_{k,j}$	The quantity of capital k demanded by industry j
$csubstp_j$	Capital input substitution parameter for industry j
desiredplabour	Desired price of labour in response to relative supply and demand
effectplabour	Price change effect for labour
$factorsd_{h,j}$	Quantity of factor h demand within industry j
$factorss_{h,j}$	Quantity of factor h supply within industry j
labratio	Ratio of total labour supply to total labour demand
$qcapitald_j$	Quantity of composite capital demand as derived from the calculated demands for individual capital types

Constants

CDPLAB	Change delay for labour price
LOOKUPLAB	Lookup function determining the scalar to apply to $Pfact_{Lab,j}$ given relative supply and demand
$SCALECC_j$	Scale parameter for industry j within the CES function for composite capital
$SHARECC_{j,k}$	Share parameter for industry j and capital k within the CES function for composite capital
TIMESTEP	Iteration time step applied in the model

G.4.3 Equations

$$Pfact_{Lab,j}(t+dt) = Pfact_{Lab,j}(t) + changeplabour \times dt$$

where: (G.66)

$$Pfact_{Lab,j}(0) = 1$$

$$Pfact_{Cap,j}(t+dt) = Pfact_{Cap,j}(t) + pcapitaladjust_j \times dt$$

where:

$$Pfact_{Cap,j}(0) = 1 \tag{G.67}$$

$$changeplabour_j = \frac{desiredplabour_j - Pfact_{Lab,j}}{CDPLAB_j} \tag{G.68}$$

$$effectplabour_j = LOOKUPLAB_j\left(labratio_j\right) \tag{G.69}$$

$$labratio_j = \frac{factorss_j}{factorsd_j} \tag{G.70}$$

$$actualpcapital_j = \frac{\sum_k \left(capitaltyped_{k,j} \times Pcapt_{k,j}\right)}{qcapitald_j \times Prodf_{Cap}} \tag{G.71}$$

$$j \notin \{\text{CropsA, AnimsA}\} \Rightarrow qcapitald_j = SCALECC_j \times \left(\sum_k SHARECC_{j,k} \times capitaltyped_{j,k}^{\ csubstp_j}\right)^{\frac{1}{csubstp_j}} \tag{G.72}$$

$$j \notin \{\text{CropsA, AnimsA}\} \Rightarrow qcapitald_j = capitaltyped_{\text{BuildC},j}$$

G.5 Reserves Module

G.5.1 Diagrammatic Representation

The Vensim DSS® influence diagram for the Ecocycle reserves module is provided in Figure G.5.

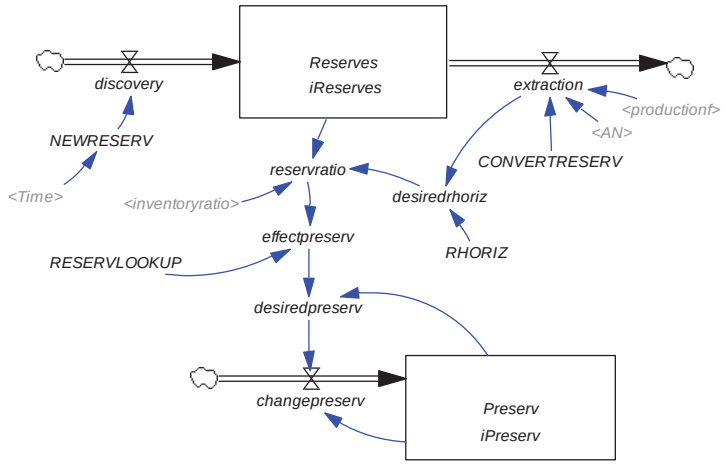

Figure G.5 Reserves Module Influence Diagram

G.5.2 Variable Definitions

Stocks

$Preserv_s$	Price of reserve *s*

$Reserves_s$	Stock of reserve s

Flows

$changepreserv_s$	Change in the price of reserve *s*
$discovery_s$	Additions to the stock of lithosphere reserve s
$extraction_s$	Extraction of reserve *s*

Converters (Excluding Constants)

$desiredrhoriz_s$	Desired size of the reserve *s* stock
$desiredpreserv_s$	Desired reserve s price
$effectpreserv_s$	Price change effect for reserve *s*
$reservratio$	Ratio of the actual stock to the desired stock for reserve *s*

Constants

$CONVERTRESERV$	Constant to convert reserve extraction in monetary terms to mass terms
$RESERVLOOKUP_s$	Lookup function determining the scalar to apply to the price of reserve *s*, given the ratio of the actual reserve stock to the desired reserve stock
$NEWRESERV_s$	Lookup function specifying the addition to reserve *s* over time
$RHORIZ_s$	Desired number of years over which reserve *s* should last

G.5.3 Equations

$$Preserv_s(t+1) = Preserv_s(t) + changepreserv_s \times dt \quad \text{(G.73)}$$

$$changepreserv_s = (desiredpreserv_s - Preserv_s) \quad \text{(G.74)}$$

$$desiredpreserv_s = effectpreserv_s \times Preserv_s \quad \text{(G.75)}$$

$$effectpreserv_s = RESERVLOOKUP_s(reservratio_s) \quad \text{(G.76)}$$

$$reservratio_s = \frac{Reserves_s}{desiredrhoriz_s} \quad \text{(G.77)}$$

$$desiredrhoriz_s = extraction_s \times RHORIZ_s \quad \text{(G.78)}$$

$$extraction_s = \sum_j (productionf_j \times AN_{j,s}) \times CONVERTRESERV_s \quad \text{(G.79)}$$

$$Reserves_s(t+1) = Reserves_v(t) + (discovery_s - extraction_s) \times dt \quad \text{(G.80)}$$

$$discovery_s = NEWRESERVES_s \quad \text{(G.81)}$$

G.6 Resources and Residuals Module

G.6.1 Variable Definitions

Stocks

$AnthrosphereC$	Stock of anthrosphere C
$AnthrosphereN$	Stock of anthrosphere N
$AnthrosphereP$	Stock of anthrosphere P
$AnthrosphereS$	Stock of anthrosphere S
$Cropresidues_e$	Stock of element e held within crop residuals
$Solidwaste_e$	Stock of element e held in solid waste
$Landfillwaste_\rho$	Stock of solid waste type ρ within landfills
$Materialuseeff_\gamma$	Efficiency of material use by industry or final demand type γ
$Residualprodeff_\gamma$	Efficiency of residual production by industry or final demand type γ
$Croplandinputeff$	Efficiency of production on croplands

Flows

cbalance	Net difference between C resource use and C residual generation
crecyclereuse	C recycled in solid wastes and crop residuals
cresiduals	Total emissions of C by industries and households as either waste or environmental commodities
cresourceuse	Total inputs of C to industries and households from the environment
croplandeffincr	Increase in cropland efficiency
$cropresidualprod_e$	Total mass of element e contained in produced crop residuals
$cropresidualloss_e$	Total mass of element e contained in crop residuals either emitted as wastes or used by sectors.
mateffincrease	Increase in material use efficiency
nbalance	Net difference between C resource use and C residual generation
nrecyclereuse	N recycled in solid wastes and crop residuals
nresiduals	Total emissions of N by industries and households as either waste or environmental commodities
nresourceuse	Total inputs of N to industries and households from the environment

pbalance	Net difference between P resource use and P residual generation
precyclereuse	P recycled in solid wastes and crop residuals
presiduals	Total emissions of P by industries and households as either waste or environmental commodities
presourceuse	Total inputs of P to industries and households from the environment
resideffincrease	Increase in efficiency of residual production
sbalance	Net difference between S resource use and S residual generation
$solidwasteloss_e$	Mass of element e contained in solid wastes that are recycled or otherwise treated
$solidwasteprod_e$	Mass of element e contained in produced solid wastes
srecyclereuse	S recycled in solid wastes and crop residuals
sresiduals	Total emissions of S by industries and households as either waste or environmental commodities
sresourceuse	Total inputs of S to industries and households from the environment

Converters (Excluding Constants)

$cctreatproducts_m^C$	Production of environmental commodity m^C via the treatment of crop residuals
$cfires_m^C$	Net loss of ecological commodity m^C through human-induced fires
$cnetuse_m^C$	Net loss of ecological commodity m^C as a result of all human activities
$cotherusenet_m^C$	Human use of ecological commodity m^C, excluding reserve extraction and human-induced fires
$creservextract_m^C$	Loss of commodity m^C via reserve extraction
$cresidbystock_\omega^C$	Emission waste or environmental commodity ω^C from economic activities
cropnpp	NPP by crops
cropnnpptobasert	Ratio of NPP by crops to base year NPP by non-crop vegetation
$cswtreatproducts_\omega^C$	Emissions of waste or environmental commodity ω^C from solid waste treatment
$cusebystock_m^C$	Total use of environmental commodity m^C by industries and households
desiredcroplandeff	Calculated cropland efficiency
$landfillemissions_\rho$	Mass of solid waste type ρ lost from landfills via emissions
$ncrtreatproducts_m^N$	Production of environmental commodity m^N via the treatment of crop residuals

$nfires_m^N$	Net loss of ecological commodity m^N through human-induced fires
$nnetuse_m^N$	Net loss of ecological commodity m^N as a result of human activities
$notherusenet_m^N$	Human use of ecological commodity m^N, excluding reserve extraction and human-induced fires
$nreservextract_m^N$	Loss of commodity m^N via reserve extraction
$nresidbystock_\omega^N$	Emission waste or environmental commodity ω^N from economic activities
$nswtreatproducts_\omega^N$	Emissions of waste or environmental commodity ω^N from solid waste treatment
$nusebystock_m^N$	Total use of environmental commodity m^N by industries and households
$othercropresidtreat_e$	Total mass of element e contained in treated crop residuals
$otherresiduse_e$	Mass of element e contained in other used crop residuals
$othersolidwastetreat_e$	Mass of element e contained in other treated solid wastes
$pctreatproducts_m^P$	Production of environmental commodity m^P via the treatment of crop residuals
$pfires_m^P$	Net loss of ecological commodity m^P through human-induced fires
$pnetuse_m^P$	Net loss of ecological commodity m^P as a result of human activities
$potherusenet_m^P$	Human use of ecological commodity m^P, excluding reserve extraction and human-induced fires
$pptoep$	Ratio of NPP by crops to economic output by the crops industry
$preservextract_m^P$	Loss of commodity m^P via reserve extraction
$presidbystock_\omega^P$	Emission waste or environmental commodity ω^P from economic activities
$productionacthhld_\gamma$	Total value of production by sector γ if γ is an industry, or total population if γ is households
$pswtreatproducts_\omega^P$	Emissions of waste or environmental commodity ω^P from solid waste treatment
$pusebystock_m^P$	Total use of environmental commodity m^P by industries and households
$reducecropd_e$	Reduced demand for element e in crops as a result of crop residual use
$scrtreatproducts_m^S$	Production of environmental commodity m^S via the treatment of crop residuals
$sfires_m^S$	Net loss of ecological commodity m^S through human-induced fires

$snetuse_m^S$	Net loss of ecological commodity m^S as a result of human activities
$solidwasterec_e$	Mass of element e contained in recycled solid wastes
$sotherusenet_m^S$	Human use of ecological commodity m^S, excluding reserve extraction and human-induced fires
$sreservextract_m^S$	Loss of commodity m^S via reserve extraction
$sresidbystock_\omega^S$	Emissions of waste or environmental commodity ω^S from economic activities
$sswtreatproducts_\omega^S$	Emissions of waste or environmental commodity ω^S from solid waste treatment
$standardresiduse_e$	Mass of element e contained in standard uses of crop residuals
$susebystock_m^S$	Total use of environmental commodity m^S by industries and households
$totalcropresiduse_e$	Total mass of element e contained in used crop residuals
$wastetofill_\rho$	Mass of solid waste type ρ sent to landfill

Constants

$CCROPTORESID_\omega^C$	Net production of environmental/waste commodity ω^C per unit of output/population for sector γ
$CCROPTORESOURCE_m^C$	Use of environmental commodity m^C per unit of crop production
$CFIREUSE_m^C$	Net use of environmental commodity m^C from human-induced fires at the base year
$CNETUSERT_{\gamma,m}^C$	Net use of environmental commodity m^C per unit of output/population for sector γ
$CRESERVSTOICH_s$	Mass of element C per unit of reserve s
$CRESIDUALRT_{\gamma,\omega}^C$	Net production of environmental/waste commodity ω^C per unit of output/population for sector γ
$LDCONVRTBASE$	Base year rental price for land
$NCROPTORESID_\omega^N$	Net production of environmental/waste commodity ω^N per unit of output/population for sector γ
$NCROPTORESOURCE_m^N$	Use of environmental commodity m^N per unit of crop production
$NFIREUSE_m^N$	Net use of environmental commodity m^N from human-induced fires at the base year
$NNETUSERT_{\gamma,m}^N$	Net use of environmental commodity m^N per unit of output/population for sector γ
$NRESERVSTOICH_s$	Mass of element N per unit of reserve s

$NRESIDUALRT_{\gamma,\omega^N}$	Net production of environmental/waste commodity ω^N per unit of output/population for sector γ
$PCROPTORESID_{\omega^P}$	Net production of environmental/waste commodity ω^P per unit of output/population for sector γ
$PCROPTORESOURCE_{m^P}$	Use of environmental commodity m^P per unit of crop production
$PFIREUSE_{m^P}$	Net use of environmental commodity m^P from human-induced fires at the base year
$PNETUSERT_{\gamma,m^P}$	Net use of environmental commodity m^P per unit of output/population for sector γ
$PRESERVSTOICH_s$	Mass of element P per unit of reserve s
$PRESIDUALRT_{\gamma,\omega^P}$	Net production of environmental/waste commodity ω^P per unit of output/population for sector γ
$SCROPTORESID_{\omega^S}$	Net production of environmental/waste commodity ω^P per unit of output/population for sector γ
$SCROPTORESOURCE_{m^S}$	Use of environmental commodity m^S per unit of crop production
$SFIREUSE_{m^S}$	Net use of environmental commodity m^S from human-induced fires at the base year
$SNETUSERT_{\gamma,m^S}$	Net use of environmental commodity m^S per unit of output/population for sector γ
$SRESERVSTOICH_s$	Mass of element S per unit of reserve s
$SRESIDUALRT_{\gamma,\omega^S}$	Net production of environmental/waste commodity ω^S per unit of output/population for sector γ
$CSWTREAT_{\omega^C}$	Emissions of environmental/waste commodity ω^C, per unit of solid waste treatment
$NSWTREAT_{\omega^N}$	Emissions of environmental/waste commodity ω^N, per unit of solid waste treatment
$PSWTREAT_{\omega^P}$	Emissions of environmental/waste commodity ω^P, per unit of solid waste treatment
$SSWTREAT_{\omega^S}$	Emissions of environmental/waste commodity ω^S, per unit of solid waste treatment
$RECYCLERT_e$	Rate of recycling for solid waste of element e
$LANDFILLEMRT$	C emission rate for solid waste
$MATEFFGRRT_\gamma$	Growth rate in material use efficiency for sector γ
$RESIDEFFGRRT\ \gamma$	Growth rate in efficiency of residual production for sector γ
$BASENPPNONCROP$	Base year NPP for non-crop vegetation

$CONVERTNPP$	Ratio of NPP to total atmospheric C use for the crop industry
$BASEYRPPTOEP$	Base year ratio of NPP by crops to economic output by the crops industry
$CCRTREAT_{m^{\mathrm{C}}}$	Emissions of environmental commodity m^{C} per unit of crop residual treatment
$NCRTREAT_{m^{\mathrm{N}}}$	Emissions of environmental commodity m^{N} per unit of crop residual treatment
$PCRTREAT_{m^{\mathrm{P}}}$	Emissions of environmental commodity m^{P} per unit of crop residual treatment
$SCRTREAT_{m^{\mathrm{S}}}$	Emissions of environmental commodity m^{S} per unit of crop residual treatment
$TOTALCRUSERT_e$	Total use rate of crop residual of element e
$ACTHHLDCRRT_\gamma$	Base year ratio of crop residual use per unit of production/ population for sector γ
$RESIDCROPQ$	Ratio of crop residual quality to standard crop quality

G.6.2 Equations

Anthrosphere C

$$AnthrosphereC(t+dt) = AnthrosphereC(t) + \begin{pmatrix} cresourceuse + crecycleuse \\ -cresiduals - cbalance \end{pmatrix} \times dt \quad \text{(G.82)}$$

$$cresourceuse = \sum_{m^{\mathrm{C}}} cusebystock_{m^{\mathrm{C}}} \quad \text{(G.83)}$$

$$cusebystock_{m^{\mathrm{C}}} = creserveextract_{m^{\mathrm{C}}} + cotheruse_{m^{\mathrm{C}}} + cfires_{m^{\mathrm{C}}} \quad \text{(G.84)}$$

$$cfires_{m^{\mathrm{C}}} = \frac{conversion}{LDCONVERTBASE} \times CFIREUSE_{m^{\mathrm{C}}} \quad \text{(G.85)}$$

$$\begin{aligned}
&m^{\mathrm{C}} = \mathrm{OceanpandcC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{FishR}} \times CRESERVSTOICH_{\mathrm{FishR}} \\
&m^{\mathrm{C}} = \mathrm{VegezoomasC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{TimberR}} \times CRESERVSTOICH_{\mathrm{TimberR}} \\
&m^{\mathrm{C}} = \mathrm{CoalC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{CoalR}} \times CRESERVSTOICH_{\mathrm{CoalR}} \\
&m^{\mathrm{C}} = \mathrm{GasC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{GasR}} \times CRESERVSTOICH_{\mathrm{GasR}} \\
&m^{\mathrm{C}} = \mathrm{PetroleumC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{PetroleumR}} \times CRESERVSTOICH_{\mathrm{PetroleumR}} \\
&m^{\mathrm{C}} = \mathrm{LithosphereC} \Rightarrow creservextract_{m^{\mathrm{C}}} = extraction_{\mathrm{CaCarbR}} \times CRESERVSTOICH_{\mathrm{CaCarbR}} \\
&m^{\mathrm{C}} \notin \{\mathrm{OceanpandcC, VegezoomasC, CoalC, GasC, PetroleumC, LithosphereC}\} \\
&\qquad \Rightarrow creservextract_{m^{\mathrm{C}}} = 0
\end{aligned} \quad \text{(G.86)}$$

$$\begin{aligned}
cotherusenet_{m^{\mathrm{C}}} = &\sum_{\gamma} \left(productionacthhld_\gamma \times \frac{CNETUSERT_{\gamma, m^{\mathrm{C}}}}{Materialuseeff_\gamma} \right) \\
&- reducedcropd_{\mathrm{C}} \times CCROPTORESOURCE_{m^{\mathrm{C}}}
\end{aligned} \quad \text{(G.87)}$$

$$crecycleuse = solidwasterec_{\mathrm{C}} + totalcropresiduse_{\mathrm{C}} \tag{G.88}$$

$$cresidbystock_{\omega^{\mathrm{C}}} = \sum_{\gamma}\left(productionacthhld_{\gamma} \times \frac{CRESIDUALRT_{\gamma,\omega^{\mathrm{C}}}}{Residualprodeff_{\gamma}} \right) - reducedcropd_{\mathrm{C}} \times CCROPTORESID_{\omega^{\mathrm{C}}} \tag{G.89}$$

$$cresiduals = \sum_{\omega^{\mathrm{C}}} cresidbystock_{\omega^{\mathrm{C}}} \tag{G.90}$$

$$cbalance = cresourceuse + crecyclereuse - cresiduals \tag{G.91}$$

Anthrosphere N

$$AnthrosphereN\left(t+dt\right) = AnthrosphereN\left(t\right) + \begin{pmatrix} nresourceuse + ncrecycleuse \\ -nresiduals - nbalance \end{pmatrix} \times dt \tag{G.92}$$

$$nresourceuse = \sum_{m^{\mathrm{N}}} nusebystock_{m^{\mathrm{N}}} \tag{G.93}$$

$$nusebystock_{m^{\mathrm{N}}} = nreserveextract_{m^{\mathrm{N}}} + notheruse_{m^{\mathrm{N}}} + nfires_{m^{\mathrm{N}}} \tag{G.94}$$

$$nfires_{m^{\mathrm{N}}} = \frac{conversion}{LDCONVERTBASE} \times NFIREUSE_{m^{\mathrm{N}}} \tag{G.95}$$

$$\begin{aligned} &m^{\mathrm{N}} = \mathrm{OceanpandcN} \Rightarrow nreservextract_{m^{\mathrm{N}}} = extraction_{\mathrm{FishR}} \times NRESERVSTOICH_{\mathrm{FishR}} \\ &m^{\mathrm{N}} = \mathrm{VegezoomasN} \Rightarrow nreservextract_{m^{\mathrm{N}}} = extraction_{\mathrm{TimberR}} \times NRESERVSTOICH_{\mathrm{TimberR}} \\ &m^{\mathrm{N}} = \mathrm{CoalN} \Rightarrow nreservextract_{m^{\mathrm{N}}} = extraction_{\mathrm{CoalR}} \times NRESERVSTOICH_{\mathrm{CoalR}} \\ &m^{\mathrm{N}} = \mathrm{PetroleumN} \Rightarrow nreservextract_{m^{\mathrm{N}}} = extraction_{\mathrm{PetroleumR}} \times NRESERVSTOICH_{\mathrm{PetroleumR}} \\ &m^{\mathrm{N}} \notin \left\{\mathrm{OceanpandcN,VegezoomasN,CoalN,PetroleumN}\right\} \Rightarrow nreserveextract = 0 \end{aligned} \tag{F.96}$$

$$notherusenet_{m^{\mathrm{N}}} = \sum_{\gamma}\left(productionacthhld_{\gamma} \times \frac{NNETUSERT_{\gamma,m^{\mathrm{N}}}}{Materialuseeff_{\gamma}} \right) - reducedcropd_{\mathrm{N}} \times NCROPTORESOURCE_{m^{\mathrm{N}}} \tag{G.97}$$

$$nrecycleuse = solidwasterec_{\mathrm{N}} + totalcropresiduse_{\mathrm{N}} \tag{G.98}$$

$$nresidbystock_{\omega^{\mathrm{N}}} = \sum_{\gamma}\left(productionacthhld_{\gamma} \times \frac{NRESIDUALRT_{\gamma,\omega^{\mathrm{N}}}}{Residualprodeff_{\gamma}} \right) - reducedcropd_{\mathrm{N}} \times NCROPTORESID_{\omega^{\mathrm{N}}} \tag{G.99}$$

$$nresiduals = \sum_{\omega^{\mathrm{N}}} nresidbystock_{\omega^{\mathrm{N}}} \tag{G.100}$$

$$nbalance = nresourceuse + nrecyclereuse - nresiduals \tag{G.101}$$

Anthrosphere P

$$AnthrosphereP\left(t+dt\right) = AnthrosphereP\left(t\right) + \begin{pmatrix} presourceuse + pcrecycleuse \\ -presiduals - pbalance \end{pmatrix} \times dt \tag{G.102}$$

$$presourceuse = \sum_{m^{\mathrm{P}}} pusebystock_{m^{\mathrm{P}}} \tag{G.103}$$

$$pusebystock_{m^{\mathrm{P}}} = preserveextract_{m^{\mathrm{P}}} + potheruse_{m^{\mathrm{P}}} + pfires_{m^{\mathrm{P}}} \tag{G.104}$$

$$pfires_{m^{\mathrm{P}}} = \frac{conversion}{LDCONVERTBASE} \times PFIREUSE_{m^{\mathrm{P}}} \tag{G.105}$$

$$\begin{aligned}
&m^{\mathrm{P}} = \mathrm{OceanpandcP} \Rightarrow preservextract_{m^{\mathrm{P}}} = extraction_{\mathrm{FishR}} \times PRESERVSTOICH_{\mathrm{FishR}} \\
&m^{\mathrm{P}} = \mathrm{VegezoomasP} \Rightarrow preservextract_{m^{\mathrm{P}}} = extraction_{\mathrm{TimberR}} \times PRESERVSTOICH_{\mathrm{TimberR}} \\
&m^{\mathrm{P}} = \mathrm{CoalP} \Rightarrow preservextract_{m^{\mathrm{P}}} = extraction_{\mathrm{CoalR}} \times PRESERVSTOICH_{\mathrm{CoalR}} \\
&m^{\mathrm{P}} = \mathrm{LithosphereP} \Rightarrow preservextract_{m^{\mathrm{P}}} = extraction_{\mathrm{PhosphateR}} \times PRESERVSTOICH_{\mathrm{PhosphateR}} \\
&m^{\mathrm{P}} \notin \{\mathrm{OceanpandcP,VegezoomasP,CoalP,LithosphereP}\} \Rightarrow preserveextract = 0
\end{aligned} \tag{G.106}$$

$$\begin{aligned}
potherusenet_{m^{\mathrm{P}}} = &\sum_{\gamma} \left(productionacthhld_{\gamma} \times \frac{PNETUSERT_{\gamma,m^{\mathrm{P}}}}{Materialuseeff_{\gamma}} \right) \\
&- reducedcropd_{\mathrm{P}} \times PCROPTORESOURCE_{m^{\mathrm{P}}}
\end{aligned} \tag{G.107}$$

$$precycleuse = solidwasterec_{\mathrm{P}} + totalcropresiduse_{\mathrm{P}} \tag{G.108}$$

$$\begin{aligned}
presidbystock_{\omega^{\mathrm{P}}} = &\sum_{\gamma} \left(productionacthhld_{\gamma} \times \frac{PRESIDUALRT_{\gamma,\omega^{\mathrm{P}}}}{Residualprodeff_{\gamma}} \right) \\
&- reducedcropd_{\mathrm{P}} \times CCROPTORESID_{\omega^{\mathrm{P}}}
\end{aligned} \tag{G.109}$$

$$presiduals = \sum_{\omega^{\mathrm{P}}} presidbystock_{\omega^{\mathrm{P}}} \tag{G.110}$$

$$pbalance = presourceuse + precyclereuse - presiduals \tag{G.111}$$

Anthrosphere S

$$AnthrosphereS(t+dt) = AnthrosphereS(t) + \begin{pmatrix} sresourceuse + screcycleuse \\ -sresiduals - sbalance \end{pmatrix} \times dt \tag{G.112}$$

$$sresourceuse = \sum_{m^{\mathrm{S}}} susebystock_{m^{\mathrm{S}}} \tag{G.113}$$

$$susebystock_{m^{\mathrm{S}}} = sreserveextract_{m^{\mathrm{S}}} + sotheruse_{m^{\mathrm{S}}} + sfires_{m^{\mathrm{S}}} \tag{G.114}$$

$$sfires_{m^{\mathrm{S}}} = \frac{conversion}{LDCONVERTBASE} \times SFIREUSE_{m^{\mathrm{S}}} \tag{G.115}$$

$$\begin{aligned}
&m^{\mathrm{S}} = \mathrm{OceanpandcS} \Rightarrow sreservextract_{m^{\mathrm{S}}} = extraction_{\mathrm{FishR}} \times SRESERVSTOICH_{\mathrm{FishR}} \\
&m^{\mathrm{S}} = \mathrm{VegezoomasS} \Rightarrow preservextract_{m^{\mathrm{S}}} = extraction_{\mathrm{TimberR}} \times SRESERVSTOICH_{\mathrm{TimberR}} \\
&m^{\mathrm{S}} = \mathrm{CoalS} \Rightarrow sreservextract_{m^{\mathrm{S}}} = extraction_{\mathrm{CoalR}} \times SRESERVSTOICH_{\mathrm{CoalR}} \\
&m^{\mathrm{S}} = \mathrm{PetroleumS} \Rightarrow sreservextract_{m^{\mathrm{S}}} = extraction_{\mathrm{PetroleumR}} \times SRESERVSTOICH_{\mathrm{PetroleumR}} \\
&m^{\mathrm{S}} = \mathrm{LithosphereS} \Rightarrow sreservextract_{m^{\mathrm{S}}} = extraction_{\mathrm{SulphurR}} \times SRESERVSTOICH_{\mathrm{SulphurR}} \\
&m^{\mathrm{S}} \notin \{\mathrm{OceanpandcS,VegezoomasS,CoalS,PetroleumS,LithosphereS}\} \Rightarrow sreserveextract = 0
\end{aligned} \tag{G.116}$$

$$\begin{aligned}
sotherusenet_{m^{\mathrm{S}}} = &\sum_{\gamma} \left(productionacthhld_{\gamma} \times \frac{SNETUSERT_{\gamma,m^{\mathrm{S}}}}{Materialuseeff_{\gamma}} \right) \\
&- reducedcropd_{\mathrm{S}} \times SCROPTORESOURCE_{m^{\mathrm{S}}}
\end{aligned} \tag{G.117}$$

$$srecycleuse = solidwasterec_{\mathrm{S}} + totalcropresiduse_{\mathrm{S}} \tag{G.118}$$

$$\begin{aligned}
sresidbystock_{\omega^{\mathrm{S}}} = &\sum_{\gamma} \left(productionacthhld_{\gamma} \times \frac{SRESIDUALRT_{\gamma,\omega^{\mathrm{S}}}}{Residualprodeff_{\gamma}} \right) \\
&- reducedcropd_{\mathrm{S}} \times SCROPTORESID_{\omega^{\mathrm{S}}}
\end{aligned} \tag{G.119}$$

$$sresiduals = \sum_{\omega^S} sresidbystock_{\omega^S} \quad \text{(G.120)}$$

$$sbalance = sresourceuse + srecyclereuse - sresiduals \quad \text{(G.121)}$$

Crop Residuals

$$Cropresidues_e(t+dt) = Cropresidues_e(t) + (cropresidualprod_e - cropresidualloss_e) \times dt \quad \text{(G.122)}$$

$$\begin{aligned} cropresidualprod_{\mathrm{C}} &= cresidbystock_{CropresidueC} \\ cropresidualprod_{\mathrm{N}} &= nresidbystock_{CropresidueN} \\ cropresidualprod_{\mathrm{P}} &= presidbystock_{CropresidueP} \\ cropresidualprod_{\mathrm{S}} &= sresidbystock_{CropresidueS} \end{aligned} \quad \text{(G.123)}$$

$$cropresidualtreat_e = totalcropresidloss_e + othercropresidtreat_e \quad \text{(G.124)}$$

$$totalcropresiduse_e = Cropresidues_e \times TOTALCRUSERT_e \quad \text{(G.125)}$$

$$otherresiduse_e = totalcropresiduse_e - standardresiduse_e \quad \text{(G.126)}$$

$$standardresiduse_e = \sum_{\gamma} \left(productionacthhd_{\gamma} \times ACTHHLDCRRT_{\gamma,e} \right) \quad \text{(G.127)}$$

$$reducedcropd_e = otherresiduse_e \times RESIDTOCROPQ \quad \text{(G.128)}$$

$$othercropresidtreat_e = Cropresidues_e - totalcropresiduse_e \quad \text{(G.129)}$$

$$ccrtreatproducts_{m^{\mathrm{C}}} = othercropresidtreat_{\mathrm{C}} \times CCRTREAT_{m^{\mathrm{C}}} \quad \text{(G.130)}$$

$$ncrtreatproducts_{m^{\mathrm{N}}} = othercropresidtreat_{\mathrm{N}} \times NCRTREAT_{m^{\mathrm{N}}} \quad \text{(G.131)}$$

$$pcrtreatproducts_{m^{\mathrm{P}}} = othercropresidtreat_{\mathrm{P}} \times PCRTREAT_{m^{\mathrm{P}}} \quad \text{(G.132)}$$

$$scrtreatproducts_{m^{\mathrm{S}}} = othercropresidtreat_{\mathrm{S}} \times CCRTREAT_{m^{\mathrm{S}}} \quad \text{(G.133)}$$

Solid Waste

$$Solidwaste_e(t+dt) = Solidwaste_e(t) + (solidwasteprod_e - solidwasteloss_e) \times dt \quad \text{(G.134)}$$

$$\begin{aligned} solidwasteprod_{\mathrm{C}} &= cresidbystock_{\mathrm{SolidwasteC}} \\ solidwasteprod_{\mathrm{N}} &= nresidbystock_{\mathrm{SolidwasteN}} \\ solidwasteprod_{\mathrm{P}} &= presidbystock_{\mathrm{SolidwasteP}} \\ solidwasteprod_{\mathrm{S}} &= presidbystock_{\mathrm{SolidwasteS}} \end{aligned} \quad \text{(G.135)}$$

$$solidwasteloss_e = solidwasterec_e + othersolidwastetreat_e \quad \text{(G.136)}$$

$$solidwasterec_e = Solidwaste_e \times RECYCLERT_e \quad \text{(G.137)}$$

$$othersolidwastetreat_e = Solidwaste_e \times (1 - RECYCLERT_e) \quad \text{(G.138)}$$

$$cswtreatproducts_{\omega^{\mathrm{C}}} = othersolidwastetreat_{\mathrm{C}} \times CSWTREAT_{\omega^{\mathrm{C}}} \quad \text{(G.139)}$$

$$nswtreatproducts_{\omega^{\mathrm{N}}} = othersolidwastetreat_{\mathrm{N}} \times NSWTREAT_{\omega^{\mathrm{N}}} \quad \text{(G.140)}$$

$$pswtreatproducts_{\omega^{\mathrm{P}}} = othersolidwastetreat_{\mathrm{P}} \times PSWTREAT_{\omega^{\mathrm{P}}} \quad \text{(G.141)}$$

$$sswtreatproducts_{\omega^{\mathrm{S}}} = othersolidwastetreat_{\mathrm{S}} \times SSWTREAT_{\omega^{\mathrm{S}}} \quad \text{(G.142)}$$

Landfill Waste

$$Landfillwaste_{\rho}(t+dt) = Landfillwaste_{\rho}(t) + \left(wastetofill_{\rho} - landfillemissions_{\rho}\right) \times dt \quad \text{(G.143)}$$

$$\begin{aligned} wastetofill_{\text{DOClandfill}} &= cresidbystock_{\text{LandfillC}} + cswtreatproducts_{\text{LandfillC}} \times 0.718 \\ wastetofill_{\text{FossilClandfill}} &= cresidbystock_{\text{LandfillC}} + cswtreatproducts_{\text{LandfillC}} \times 0.282 \\ wastetofill_{\text{Nlandfill}} &= nresidbystock_{\text{LandfillN}} + nswtreatproducts_{\text{LandfillN}} \\ wastetofill_{\text{Plandfill}} &= presidbystock_{\text{LandfillP}} + pswtreatproducts_{\text{LandfillP}} \\ wastetofill_{\text{Slandfill}} &= sresidbystock_{\text{LandfillS}} + sswtreatproducts_{\text{LandfillS}} \end{aligned} \quad \text{(G.144)}$$

$$\begin{aligned} &landfillemissions_{\text{DOClandfill}} = Landfillwaste_{\text{DOClandfill}} \times LANDFILLEMRT \\ &\rho \neq \text{DOClandfill} \Rightarrow landfillemissions_{\rho} = 0 \end{aligned} \quad \text{(G.145)}$$

Production and Material Use, Residual Production and Cropland Efficiency

$$\begin{aligned} &\gamma \in \{\text{Ind1, Ind2, ..., Ind}\pi\} \Rightarrow productionacthhld_{\gamma} = productionf_{j} \\ &\gamma = \text{Hhlds} \Rightarrow productionacthhld_{\gamma} = population \\ &\gamma \in \{\text{Govnt, Savgs}\} \Rightarrow productionacthhld_{\gamma} = 0 \end{aligned} \quad \text{(G.146)}$$

$$Materialuseeff_{\gamma}(t+dt) = Materialuseeff_{\gamma}(t) + mateffincrease_{\gamma} \times dt \quad \text{(G.147)}$$

$$mateffincrease_{\gamma} = Materialuseeff_{\gamma} \times MATEFFGRRT_{\gamma} \quad \text{(G.148)}$$

$$Residualprodeff_{\gamma}(t+dt) = Residualprodeff_{\gamma}(t) + resideffincrease_{\gamma} \times dt \quad \text{(G.149)}$$

$$resideffincrease_{\gamma} = Residualprodeff_{\gamma} \times RESIDEFFGRRT_{\gamma} \quad \text{(G.150)}$$

$$Croplandinputeff(t+dt) = Croplandinputeff(t) + croplandeffincr \times dt \quad \text{(G.151)}$$

$$croplandeffincr = \left(desiredcroplandeff - Croplandinputeff\right) \times \frac{1}{TIMESTEP} \quad \text{(G.152)}$$

$$desiredcroplandeff = \frac{BASEYRPPTOEP}{pptoep} \quad \text{(G.153)}$$

$$pptoep = \frac{productionacthhld_{\text{CropsAF}} \times \frac{CNETUSERT_{\text{CropsAF,AtmosnecC}}}{Materialuseeff_{\text{CropsAF}}} - reducedcropd_{\text{C}} \times CCROPTORESOURCE_{\text{AtmosnecC}}}{productionacthhld_{\text{CropsAF}}} \quad \text{(G.154)}$$

$$\begin{aligned} cropnpp = productionacthhld_{CropsA} &\frac{CNETUSERT_{CropsAF,AtmosnecC}}{Materialuseeff_{CropsAF}} \\ &- reducedcropd_{C} \times CCROPTORESOURCE_{AtmosnecC} \times CONVERTNPP \end{aligned} \quad \text{(G.155)}$$

$$cropnpptibasert = \frac{cropnpp}{BASENPPNONCROP} \quad \text{(G.156)}$$

Net Use of Ecological Commodities

$$
\begin{aligned}
cnetuse_{\text{AtmosnecC}} &= cusebystock_{\text{AtmosnecC}} - cswtreatproducts_{\text{AtmosnecC}} - ccrtreatproducts_{\text{AtmosnecC}} \\
&\quad - cresidbystock_{\text{AtmosnecC}} - landfillemissions_{\text{DOClandfill}} - cbalance \\
cnetuse_{\text{SoilC}} &= cusebystock_{\text{SoilC}} - cswtreatproducts_{\text{SoilC}} - ccrtreatproducts_{\text{SoilC}} - cresidbystock_{\text{SoilC}} \\
cnetuse_{\text{DetritusC}} &= cusebystock_{\text{DetritusC}} - cswtreatproducts_{\text{DetritusC}} - ccrtreatproducts_{\text{DetritusC}} \\
&\quad - cresidbystock_{\text{DetritusC}} \\
m^{\text{C}} \in &\left\{\begin{array}{l}\text{OceanpandcC, OceannecC,}\\ \text{OceanhumusC, VegezoomasC,}\\ \text{OceancalcarbC, CoalC, GasC,}\\ \text{PetroleumC, LithosphereC}\end{array}\right\} \Rightarrow cnetuse_{m^{\text{C}}} = cusebystock_{m^{\text{C}}} - ccrtreatproducts_{m^{\text{C}}}
\end{aligned}
\tag{G.157}
$$

$$
\begin{aligned}
nnetuse_{\text{AtmosnecN}} &= nusebystock_{\text{AtmosnecN}} - nswtreatproducts_{\text{AtmosnecN}} - ncrtreatproducts_{\text{AtmosnecN}} \\
&\quad - nresidbystock_{\text{AtmosnecN}} \\
nnetuse_{\text{Atmos2N}} &= nusebystock_{\text{Atmosn2N}} - nswtreatproducts_{\text{Atmosn2N}} - ncrtreatproducts_{\text{Atmosn2N}} \\
&\quad - nresidbystock_{\text{Atmosn2N}} \\
nnetuse_{\text{DetritusN}} &= nusebystock_{\text{DetritusN}} - nswtreatproducts_{\text{DetritusN}} - ncrtreatproducts_{\text{DetritusN}} \\
&\quad - nresidbystock_{\text{DetritusN}} - nbalance \\
nnetuse_{\text{SoilN}} &= nusebystock_{\text{SoilN}} - nswtreatproducts_{\text{SoilN}} - ncrtreatproducts_{\text{SoilN}} - nresidbystock_{\text{SoilN}} \\
m^{\text{N}} \in &\left\{\begin{array}{l}\text{OceanpandcN, OceannecN,}\\ \text{OceanhumusN, VegezoomasN,}\\ \text{CoalN, PetroleumN, LithosphereN}\end{array}\right\} \Rightarrow nnetuse_{m^{N}} = nusebystock_{m^{\text{N}}} - ncrtreatproducts_{m^{\text{N}}}
\end{aligned}
\tag{G.158}
$$

$$
\begin{aligned}
pnetuse_{\text{DetritusP}} &= pusebystock_{\text{DetritusP}} - pswtreatproducts_{\text{DetritusP}} - pcrtreatproducts_{\text{DetritusP}} \\
&\quad - presidbystock_{\text{DetritusP}} - pbalance \\
pnetuse_{\text{Soilp}} &= pusebystock_{\text{SoilP}} - pswtreatproducts_{\text{SoilP}} - pcrtreatproducts_{\text{SoilP}} - presidbystock_{\text{SoilP}} \\
m^{\text{N}} \in &\left\{\begin{array}{l}\text{OceanpandcP, OceannecP,}\\ \text{OceanhumusP, VegezoomasP,}\\ \text{CoalP, LithosphereP}\end{array}\right\} \Rightarrow nnetuse_{m^{N}} = nusebystock_{m^{\text{N}}} - ncrtreatproducts_{m^{\text{N}}}
\end{aligned}
\tag{G.159}
$$

$$
\begin{aligned}
snetuse_{\text{AtmosnecS}} &= susebystock_{\text{AtmosnecS}} - sswtreatproducts_{\text{AtmosnecS}} - scrtreatproducts_{\text{AtmosnecS}} \\
&\quad - sresidbystock_{\text{AtmosnecS}} \\
snetuse_{\text{SoilS}} &= susebystock_{\text{SoilS}} - sswtreatproducts_{\text{SoilS}} - scrtreatproducts_{\text{SoilS}} - sresidbystock_{\text{SoilS}} \\
snetuse_{\text{DetritusS}} &= susebystock_{\text{DetritusS}} - sswtreatproducts_{\text{DetritusS}} - scrtreatproducts_{\text{DetritusS}} \\
&\quad - sresidbystock_{\text{DetritusS}} - sbalance \\
m^{\text{N}} \in &\left\{\begin{array}{l}\text{OceanpandcS, OceannecS,}\\ \text{OceanhumusS, VegezoomasS,}\\ \text{CoalS, PetroleumS, LithosphereS}\end{array}\right\} \Rightarrow nnetuse_{m^{N}} = nusebystock_{m^{\text{N}}} - ncrtreatproducts_{m^{\text{N}}}
\end{aligned}
\tag{G.160}
$$

G.7 Summary of Model Arrays

Table G.1 provides a summary of the elements included within each of the arrays defined within the Ecocycle model. For brevity, the environmental processes and stocks are excluded from Table G.1. A summary of the different environmental processes and stocks included within the model is available in Tables 8.1 and 8.2 of Chapter 8.

Table G.1 Arrays within the Ecocycle Model

Full Commodities (subscript i)		Short Commodities (subscript i^*)		Activities (subscript j)		Sectors (subscript γ)	
Code	Description	Code	Description	Code	Description	Code	Description
CropsFC	Crops	CropsSC	Crops	CropsA	Crops	CropsAF	Crops
AnimsFC	Animals and unprocessed animal products	AnimsSC	Animals and unprocessed animal products	AnimsA	Animals and unprocessed animal products	AnimsAF	Animals and unprocessed animal products
ForstFC	Forestry	ForstSC	Forestry	ForstA	Forestry	ForstAF	Forestry
CoalFC	Coal	FofibSC	Food and fibre products	CoalfA	Coal	CoalfAF	Coal
OilffFC	Oil	WdpapSC	Wood and paper products	OilffA	Oil	OilffAF	Oil
GasffFC	Gas and gas distribution	ChminSC	Chemical and mineral manufacturing	GasffA	Gas and gas distribution	GasffAF	Gas and gas distribution
FofibFC	Food and fibre products	OmanfSC	Other manufacturing	FofibA	Food and fibre products	FofibAF	Food and fibre products
WdpapFC	Wood and paper products	WaterSC	Water	WdpapA	Wood and paper products	WdpapAF	Wood and paper products
PetrlFC	Petroleum manufacturing	ConstSC	Construction	PetrlA	Petroleum manufacturing	PetrlAF	Petroleum manufacturing
ChminFC	Chemical and mineral manufacturing	TrnspSC	Transport	ChminA	Chemical and mineral manufacturing	ChminAF	Chemical and mineral manufacturing
OmanfFC	Other manufacturing	ServsSC	Services	OmanfA	Other manufacturing	OmanfAF	Other manufacturing
ElectFC	Electricity	EnergSC	Energy	ElectA	Electricity	ElectAF	Electricity
WaterFC	Water			WaterA	Water	WaterAF	Water
ConstFC	Construction			ConstA	Construction	ConstAF	Construction
TrnspFC	Transport			TrnspA	Transport	TrnspAF	Transport
ServsFC	Services			ServsA	Services	ServsAF	Services
						HhldsAF	Households
						GovntAF	Government
						SavgsAF	Savings and investment

Table G.1 Arrays within the Ecocycle Model (Cont.)

Energy (subscript g)		Fuels (subscript f)		Crop Types (subscript c)		Capital Types (subscript k)	
Code	Description	Code	Description	Code	Description	Code	Description
ElectEF	Electricity	CropFL	Crops	CropEN	Energy crops	BuildC	Non-land capital
FuelsEF	Fuels	CoalFL	Coal	CropFF	Food and fibre crops	LandC	Land
		OilfFL	Crude oil				
		GasfFL	Gas				
		PetrFL	Petroleum				

Table G.1 Arrays within the Ecocycle Model (Cont.)

Factors (subscript h)		Input Types (subscript λ)		Environmental Reserves (subscript s)		Landfill Types (subscript ρ)	
Code	Description	Code	Description	Code	Description	Code	Description
Cap	Capital	InterI	Intermediate inputs	PetroleumR	Petroleum	DOClandfill	Degradable organic C landfill waste
Lab	Labour	FactsI	Factor inputs	GasR	Gas	FossilClandfill	Fossil C landfill waste
				FishR	Fish	Nlandfill	N landfill waste
				TimberR	Timber	Slandfill	S landfill waste
				CaCarbR	Calcium carbonate minerals	Plandfill	P landfill waste
				PhosphateR	Phosphate minerals		
				SulphurR	Sulphur minerals		

Table G.1 Arrays within the Ecocycle Model (Cont.)

C Wastes and Residuals		N Wastes and Residuals		P Wastes and Residuals		S Wastes and Residuals	
Code	Description	Code	Description	Code	Description	Code	Description
wAtmosnecC	Atmosphere C	wAtmosn2N	Dinitrogen	wDetritusP	Litter and detritus P	wAtmosnecS	Atmosphere S
wDetritusC	Litter and detritus C	wAtmosnecN	Other atmosphere N	wSoilP	Other soil P	wDetritusS	Litter and detritus S
wSoilC	Other soil C	wDetritusN	Litter and detritus N	wLandfillP	Landfill waste P	wSoilS	Other soil S
wLandfillC	Landfill waste C	wSoilN	Other soil N	wCropresidueP	Crop residuals P	wLandfillS	Landfill waste S
wCropresidueC	Crop residuals C	wLandfillN	Landfill waste N	wSolidwasteP	Solid waste P	wCropresidueS	Crop residuals S
wSoildwasteC	Soild waste C	wCropresidueN	Crop residuals N			wSolidwasteS	Solid waste S
		wSolidwasteN	Solid waste N				

Appendix H

Contents of Accompanying CD-ROM

Please find enclosed in the inside back cover of this thesis a CD-ROM containing the following files:

Chapter 4

Material Flow Accounts for the Global Economy.xlsx

Chapter 5

C, N, P and S Flows.xlsx

Chapter 7

Dynamic General Equilibrium Seeming Model with Constant Factors.mdl

Dynamic General Equilibrium Seekign Model with Factor Growth.mdl

Chapter 8

Dynamic Global Biogeochemical Cycling Model.mdl

Environment.cin

Chapter 9

Global Orchestration Scenario

- Ecocycle Model GO Scenario.mdl
- Economic.cin
- Environment.cin

TechnoGarden Scenario

- Ecocycle Model TG Scenario
- Economic.cin
- Environment.cin

Appendix I

Administration Forms

Erratum

Table EM.1 lists a set of additional footnotes that have been added to the thesis *Sustainability and the Global Biogeochemical Cycles: Integrated modelling of coupled economic and environmental systems* at the pages indicated. These footnotes improve the thesis by providing further information and improved clarity to explanations provided within the document. Table EM.2 lists a set of further corrections to the thesis.

Table EM.1 Additional Footnotes

Page	Footnote No.	Footnote Text
52	36a	The contribution of Hannon (1973) is particularly relevant to this thesis, as it relies an IO-type framework to describe environmental systems, including production and respiration energy flows between ecosystem 'compartments'.
53	37a	Strictly speaking SUTs may also be used directly within analytical models, that is without first transforming to IO tables. In these situations the assumptions regarding the relationships between industry outputs and commodities are incorporated within the analytical model itself (see Miller and Blair (2009, pp. 188-222) for a mathematical explanation).
55	38a	Isard *et al*. (1967) and Daly (1968) were the first to represent the environment-economy system in this form, proposing a framework with sub-compartments describing interactions *within* the environment system as well as flows *between* the environment and economy - refer also to Appendix A.
55	39a	Refer to Lenzen and Schaeffer (2004) for a comprehensive literature review on the evolution of SAMs, including environmentally-extended SAMs and the associated applications.
194	139a	The symmetric IO structure is also chosen on the basis that the available economic data within the GTAP 7.0 database does not include joint production, and hence is effectively a symmetric structure. Note, however, that further development of the DGES model beyond this thesis has included modification to allow for a SUT structure allowing for multiple commodities to be produced by an industry.
223	148a	The author of this thesis is currently in the process of developing alternative versions of the DGES model, including a version that incorporates international trade of commodities via utilisation of the so-called 'Armington' assumption, as well as the possibility for multiple types of economic commodities to be produced by each industry.
227	151a	In Dutch the *Planbureau voor de Leefomgeving* (PBL).
270	217a	As the scenario narratives did not provide a detailed description of the future changes in inputs, outputs and production technologies for each type of economic activity or industry within the global economy, it was considered too uncertain to run the scenarios out for 100 years within the modelling framework.
279	217b	The sharp increase in overshoot of river export for the N and P cycles, and also ocean NPP in the case of the P cycle, is of particular concern as it warns of likely high rates of growth in the incidence of freshwater, estuarine and coastal eutrophication.

Table EM.2 Other Corrections

Page	Location	Correction
53	Second line of Section 3.3.2	Replace 'PIOTs' with 'Physical Input Output Tables (PIOTs)'
57	Figure 3.4	Replace row title 'Final Demands' with 'Value Added'
71	Footnote 50	Add to the end of the footnote: There are a number of other recent iniatives aimed at assempling large-scale global multi-regional IO tables or frameworks, often complemented with information on resources flows and/or environmental burdens. Reference can be made, in particular, to the March 2013 special issue of the journal Economic Systems Research (vol. 25, issue 1).
106,107	Table 4.13	An additional note is added to Table 4.13: 2. All C fluxes are in Tg while N, P and S fluxes are in Gg.
171	First paragraph	The following sentence is added to the end of the paragraph: Put another way, it takes over 20 years for the natural system to 'alleviate or 'undo' the additional demand for terrestrial C processes caused by just one year of human activity.
257	Figure 9.2	The following note is added to Figure 9.2: Composite energy is treated as one of the *n* different commodities that together form the composite item 'Intermediate Goods'.
276	Second paragraph	Replace 'Recall that Ecotime does not contain separate freshwater stocks and a significant proportion of soil N is likely to be unavailable to terrestrial vegetation' with 'Recall that Ecotime groups both soil and freshwater stores of an element within the 'soil' stock, and a significant proportion of the reactive N accumulated is likely to be within freshwater and hence unavailable to terrestrial vegetation'.
330	After reference beginning 'Isard, W.'	Add references: Isard, W., Bassett, K., Choguill, C., Furtado, J., Izumita, R., Kissin, J., Romanoff, E., Seyfarth, R. & Tatlock, R. (1967). On the linkage of socio-economic and ecological systems. *Papers and Proceedings of the Regional Science Association* , *21* , 79-99. Isard, W., Choguill, C.L., Kissin, J., Seyfarth, R.H., Tatlock, R., Bassett, K.E., Furtado, J.G. & Izumitam R.M. (1972) *Ecological-economic analysis for regional development* . New York, NY: THe Free Press. Isard, W. & Langford, T.W. (1971). Some new directions: Environmental quality analysis and standardization. *Regional Input-Output Study: Recollections, Reflections, and Diverse Notes on the Philadelphia Experience.* Cambridge, MA: The MIT Press, 203-222.
336	Start of page	Add reference: Lenzen, M. & Schaeffer, R. (2004). Environmental and Social Accounting for Brazil. *Environmental and Resource Economics* , *27* , 201-226.
336	After reference beginning 'Leontief, W. (1970)'	Add reference: Leontief, W. & Ford, D. (1970). Environmental repercussions and the economic structure: an input-output approach. *Review of Economics and Statistics* , *52* , 262-271.
380	Second paragraph	Replace 'Isard's (1968) model' with 'Isard's (1968) model, preceeded by Isard *et al* . (1967)'
378	First paragraph	Replace 'Leontief's (1970) environmental IO model' with 'Leontief's environmental IO model (Leontief, 1970; Leontief and Ford (1970))'.
381	First paragraph	Replace last sentence of first paragraph with: Isard and his co-workers expended considerable effort demonstrating the operation of the model via selected case studies (Isard *et al* . 1967, Isard 1968, Isard and Langford 1971, Isard *et al* . 1972). Nevertheless, one of the major criticisms of the approach is that the data required to complete the coefficients is not generally available.