An environmentally-based systems approach to sustainability analyses of organic fruit production systems in New Zealand

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ABSTRACT

An environmentally-based systems approach to sustainability analyses of organic fruit production systems in New Zealand

This research introduces an approach for the assessment of the sustainability of farming systems. It is based on the premises that sustainability has an environmental bottom line and that there is very limited substitutability between natural capital and other forms of capital. Sustainability assessment is undertaken through analyses of energy and material flows of the system and their impacts on the environment. The proposed sustainability assessment approach is based on two high level criteria for sustainability: efficient use of energy and non-degradation of the environment from energy and material use.

Sustainability assessment of organic orchard systems in New Zealand was undertaken to demonstrate this approach. Five indicators which address the two criteria for the sustainability of the orchard systems are the energy ratio, the CO_2 ratio, changes in the soil carbon level, nutrient balances, and the leaching of nitrogen. Organic kiwifruit and organic apple systems are modelled based on their key energy and material flows and their interactions with the natural environment. The energy and material flows are converted into appropriate energy and matter equivalents based on coefficients taken from the published literature. Sustainability indicators are estimated over one growing season using two computer modelling tools, Overseer® and Stella®, in a life cycle approach.

Sustainability assessment of the organic orchard systems suggests that the approach is useful for evaluating energy use and key environmental impacts that occur in soil, water and atmosphere. The results indicate that the model organic orchard systems are sustainable in terms of energy use and are a net sink of CO_2-equivalent emissions. The implication of this result is that organic orchard systems potentially could trade carbon credits under the Kyoto Protocol. The findings also suggest that the sustainability assessment approach is capable of identifying the trade-offs within the sustainability indicators associated with particular management practices. Further research to improve and validate the proposed approach is essential, before it can be practically used for decision making at the orchard level and for policy making at the national level.

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INTRODUCTION

1.1 Introduction

The sustainability of agricultural systems has been a focus of much debate in research and policy since the 1970s. Even so, assessment of agricultural sustainability remains an elusive concept in both arenas. This is because sustainability has been interpreted mainly from economic, social and environmental perspective. As economic growth occurs at the cost of environmental impacts, interpretations of sustainability imply a conflict between environmental and socio-economic concerns. Although social and economic considerations are important, sustainability essentially has an environmental bottom line. The natural environment is characterised by finite resources and threshold levels beyond which systems change dramatically. These levels and the finiteness of resources are not mitigated by socio-economic concerns.

The research reported here is based on the concept of strong sustainability, which is rooted in thermodynamics and gives utmost priority to environmental sustainability. A modelling framework using computer modelling tools is proposed for sustainability assessment, with applications to organic kiwifruit and organic apple systems in New Zealand. The aim in this chapter is to describe the research context and to briefly explain the structure of this thesis.

1.2 Background

Environmental degradation around the world is accelerating to the point that human activities are having irreversible impacts on the environment (Millennium Ecosystem Assessment, 2005). Rapid industrialisation, which is dependent on fossil fuels, produces wastes and residuals that exceed the assimilative capacities of nature and results in alterations to global climate and deterioration of land, air and water in many parts of the world. Over recent times, agriculture has been one of the important human activities associated with environmental degradation. In the past 100 years alone, agriculture has been drastically transformed from a resource-based subsistence activity to a highly technological, commercial, industrial and resource-demanding enterprise. Intensification of agriculture to keep pace with the growing food demand (more output per unit of land or labour) has led to negative impacts on the environment. The general tendency globally has been increased productivity through increased intensity of inputs, with little consideration for environmental damage.

Environmental sustainability is central to the agricultural sustainability debate. Agriculture is a major land user globally (OECD, 1996). Agricultural activities put pressure on the environment by consuming higher quantities of resources and releasing wastes/residuals, which often result in adverse impacts on the environment. The environmental problems associated with agriculture include soil degradation, climate change, biodiversity loss, desertification, and polluted waters. Soils are being lost at rapid rates. Monoculture increases vulnerability to pests and diseases and reduces biodiversity (PCE, 2004). Degradation in ground water quality is associated with nutrient losses through leaching. Fossil energy use is a major input in agriculture, which releases greenhouse gases (GHG) into the atmosphere. Degradation of agricultural land requires even more intensive practices to maintain productivity, with higher inputs of fertilisers and chemicals, many of which are manufactured from non-renewable resources and the use of which results in negative environmental impacts (Pimentel & Wen, 1990). Thus, conventional agricultural practices exploit the very environmental resources agriculture is based upon. It appears that the high productivity of intensive agriculture may not be sustainable in the long term because of degradation of environmental quality and depletion of natural resources (Conway, 1987; Reganold et al., 2001; Millennium Ecosystem Assessment, 2005).

The Brundtland Report, published in 1987 by the World Commission on Environment and Development created widespread awareness of ‘sustainability’, and developed an interest in the topic internationally (WCED, 1987). In the report, sustainability is described as maintaining the conditions of the economy, society and the environment so that the future generations have the same opportunities as present generations. Although it is generally accepted that sustainability is achieved when the economic, social and environmental conditions are fulfilled, the emphasis given to each of these components varies greatly across individuals, organisations and governments. The conflict between economic growth and maintaining environmental integrity remains today because of the fact that economic growth often occurs at the cost of negative impacts on the environment (WCED, 1987; Blaschke et al., 1991).

Indefinite economic growth is not possible in a biophysically finite Earth. In the biophysical sense, the sustainability of economic systems depend on the continuous flow of energy and material inputs into the systems from the biosphere, and on the ability of the biophysical environment to absorb and purify wastes produced by the economy. Therefore, to achieve sustainability it is required that human activities should be kept to the level that ensures that the wastes produced by the economy do not exceed the assimilative capacity of the environment (Adams, 2006).

Environmental sustainability is a prerequisite for the sustenance of all human activities, including agriculture (Daly, 1991; Goodland & Daly, 1996). The sustainability of human economic systems such as agriculture is ultimately constrained by the maintenance of a healthy environment in two ways: the environment is a source of natural resources, and the environment is a sink for wastes. Additionally, the environment also provides the basic life support systems on the Earth. The provision and purification of clean air and water, nutrient cycling, genetic diversity for food crops, pollination, shielding of ultra-violet radiation by the ozone layer, and climate regulation are all essential for human survival, and these cannot be replaced by human endeavour.

This research is motivated by the premise that if agricultural practices degrade the environment, they cannot be sustainable. Such a view is captured by the concept of strong sustainability. In strong sustainability, the utmost priority is accorded to the maintenance of healthy environmental conditions. The rationale for choosing strong sustainability as the theoretical foundation for the development of a sustainability assessment framework is based on the fact that a healthy environment is the basis for other kinds of sustainability. Environmental degradation might have uncertain and potentially irreversible consequences on the basic life support system on the Earth, and therefore on the continuation of any human activities (Daly, 1991; PCE, 2002; Stoneham et al., 2003).

1.3 Research context

The importance of agriculture to quality of life has stimulated a demand for better understanding as to agricultural sustainability. Sustainability assessment is an important tool to guide the journey towards sustainability. Even so, sustainability assessment remains an elusive concept because there are various ways in which agricultural sustainability is interpreted by analysts.

Better understanding of how to achieve sustainability of an individual farming system is important, as it is at this level that most changes can be made to reduce the environmental impacts of farming activities. Thus, practical assessment of sustainability at the farm level is essential for making progress in the journey to sustainability. The theory of thermodynamics provides insights which have implications for environmental degradation and sustainability. However, there is presently no practical framework based on the theory of strong sustainability – which is rooted in thermodynamics, and which is applicable to study sustainability at the farming systems level.

It is generally accepted that organic farming systems are gentler on the Earth, and therefore are more sustainable than their conventional counterparts. Organic farming is considered as an option to achieve agricultural sustainability (MAF, 1994b). In practice, however, this view of a close relationship between organic agriculture and sustainability is not universal (Reganold et al., 1990; Rigby & Caceres, 2000; Edwards-Jones & Howells, 2001). Organic agriculture does not mean zero environmental impacts.

Kiwifruit and apple systems in New Zealand are coming under increasing pressure to grow quality fruit with minimum environmental damage if New Zealand is to continue exporting to the Northern hemisphere. However, there is no consensus as to whether or not organic kiwifruit and organic apple systems in New Zealand are sustainable. There is general public awareness that agricultural practices should become more sustainable. Identifying whether these systems are in fact sustainable can contribute to the security of overseas marketing of organic kiwifruit and apples from New Zealand. These issues lead to the overall aim addressed in this research, which is to develop a practical approach based on strong sustainability to assess sustainability at the orchard systems level. To fulfil this aim, the following research questions need to be answered:

1. What constitutes sustainability at the orchard systems level?
2. How can sustainability be assessed at the orchard systems level?

The proposed framework for sustainability assessment was developed based on the literature of strong sustainability and thermodynamics, and applied to organic kiwifruit and organic apple systems in New Zealand. The application of the proposed sustainability assessment to these systems served two purposes: first, it helped to identify whether the approach is appropriate for assessing sustainability; and second, it contributed to the greater understanding into the sustainability of these systems. Thus, two further research questions are addressed in this research:

3. How well does the proposed approach work for assessing sustainability?
4. What are the key factors that influence the sustainability of organic kiwifruit and organic apple systems in New Zealand?

The above research questions are addressed through achievement of the following research objectives:

1. To define the criteria for evaluating sustainability at the orchard system level

2. To describe indicators satisfying the criteria for strong sustainability at the orchard system level
3. To model organic kiwifruit and organic apple production systems in New Zealand
4. To develop a method for assessing the sustainability of these model systems
5. To undertake key management scenario analyses and sensitivity analyses to identify how well the model responds to changes in model inputs

The theoretical concept for sustainability assessment is developed from the literature on strong sustainability and thermodynamics. Various approaches to sustainability assessment and the major impacts of agriculture on the environment were reviewed. From this review, an analytical framework for assessing organic orchard systems sustainability was developed, and appropriate indicators were proposed. Primary data on orchard production practices were gathered directly from the growers in order to model typical organic kiwifruit and organic apple production systems. Parameters gathered from the published literature were used to convert primary data in order to estimate sustainability indicators. Practical assessment was carried out with two computer modelling tools, the Overseer® nutrient budget and Stella® modelling tool, which were used to estimate the sustainability indicators of organic orchard systems. In order to identify how well the approach works for assessing sustainability, management scenario analyses and sensitivity analyses were undertaken.

1.4 Thesis organisation

In this chapter the background to the problem and context of the research are described, and the aim and objectives for the investigation are proposed. In Chapter Two, the theoretical background for sustainability is presented. The case for strong sustainability is made in this chapter and the essential criteria for sustainability are identified. The aim in Chapter Three is to present the sustainability assessment approach based on strong sustainability that is practically applicable at the orchard systems level. In order to do this, different approaches to sustainability assessment and the key impacts of agriculture on the environment are reviewed. In Chapter Four, the methodology for the application of the proposed sustainability assessment is described. This includes the explanation of the primary and published data, and the computer modelling tools. In Chapters Five and Six, the results from the application of the proposed sustainability assessment approach to the organic kiwifruit and organic apple systems respectively are presented. In Chapter Seven, the key findings of this research are discussed, and conclusions and implications are presented.

Chapter 2

UNDERSTANDING SUSTAINABILITY

2.1 Introduction

Sustainability means different things to different people, at different periods of time. As such, the term sustainability is a popular buzzword in the academic field and also in public policy concerned with the environment. Although sustainability interpretations have varied, it is generally accepted that in order to achieve sustainability, the economic, social and environmental conditions have to be met.

The conflict between meeting socio-economic and environmental conditions continues, because economic growth largely occurs at the cost of negative environmental impacts. In recent times, agriculture has been an important human activity that has negatively impacted on the environment. Negative environmental impacts, beyond the Earth’s assimilative capacity, might have catastrophic effects on the very sustenance of agricultural enterprise. This suggests that although socio-economic activities are important, the sustainability of agricultural enterprises is ultimately constrained by the non-degradation of the environment.

The focus in this chapter is on describing the thermodynamic interpretations of sustainability, which have implications on environmental degradation. The various ways in which agricultural sustainability is interpreted is described and how they are related to the laws of thermodynamics is discussed. Strong sustainability, which is rooted in thermodynamics, is considered an appropriate worldview for achieving sustainability. The theoretical principles for strong sustainability that underpin this research are also described.

2.2 Sustainability concepts

Since the 1980s, there has been a prolific production of sustainability-related literature. A commonly quoted definition of sustainable development remains the one proposed by the World Commission on Environment and Development, popularly called the Brundtland Report. This report describes sustainable development as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 43). However, the definition proposed in the Brundtland report does not articulate the concept of ‘needs’ and the mechanisms for achieving a sustainable society (World Bank, 2003; Castro, 2004). In fact, after the publication of this report, numerous definitions of sustainability have been suggested, yet none have been universally accepted, therefore making ‘sustainability’ merely a catchword (Custance & Hillier, 1998; Tellegen, 2006).

Agricultural sustainability has been defined in different ways, to suit the varied interests of different groups of people. There are some common themes throughout these definitions, which include protection of ecosystems and biodiversity, improvements in the quality of life, inter- and intra-generational equity, and maintaining a standard of living. Although the general definition of agricultural sustainability touches upon areas of economic, social and environmental development, the emphasis given to each of these aspects has varied greatly (Douglass, 1984; Yunlong & Smit, 1994). As a result, agricultural sustainability is interpreted from three different viewpoints: economic, social, and environmental (Douglass, 1984; Brown et al., 1987; Pannell & Schilizzi, 1999). These are further described below.

2.2.1 Predominantly economy-oriented perspective

Sustained yields and economic performance are at the heart of the economy-oriented perspective of agricultural sustainability (Yunlong & Smit, 1994). The minimum condition for sustainable agriculture, under this perspective, is that total food production always meets the needs of the global population. The idea behind this condition is that the food supply should always satisfy the demand (Raman, 2006). Sustainability, from the predominantly economy-oriented perspective, is primarily concerned with long-term economic benefits to agricultural producers. Agriculture is not considered sustainable if farms are unable to generate sufficient profits; the farms have low farm product prices i.e. the yield is reduced; and/or the cost of production increases.

In the predominantly economy-oriented perspective, biophysical limits of the environment to provide resources are not considered as a constraint to increase the output of particular goods or services, insofar as society is willing to incur the economic and environmental costs. It is believed that, even if the natural capacity of the land to provide resources is lowered, yield can be maintained by substituting artificially made inputs for naturally available nutrients (Douglass, 1984; Zinck et al., 2004). Thus, scientific research and technological development are counted on to increase yield, even under the condition of degradation within the environment.

2.2.2 Predominantly society-oriented perspective

People identifying with the predominantly society-oriented perspective believe that, in order to be sustainable, agriculturalists should be socially responsible and take into account the welfare of all those people who depend on agriculture. It is expected that, through sustainable agriculture, the welfare of society is achieved by the satisfaction of basic human needs, such as food and shelter and social and cultural requirements, such as security, equity, freedom, education, employment and recreation, are met (Brown et al., 1987; Zinck et al., 2004).

Enhancement of the values of the community is given utmost importance in the predominantly society-oriented perspective of sustainable agriculture. A community is considered to be made up of individuals who affect one another through patterns of experiences (Douglass, 1984). The richness of relationships between individuals is valued more than the traditional standards of wealth, success and status. Aspects of social justice and equity, including intragenerational equity and intergenerational equity, are considered to be at the heart of agricultural sustainability in this predominantly society-oriented perspective.

2.2.3 Predominantly environment-oriented perspective

Agricultural production systems, that cause environmental degradation, are not considered sustainable in the predominantly environment-oriented perspective (Yunlong & Smit, 1994). In this perspective, the enhancement of the physical conditions of natural resources, namely soil, air, water and biodiversity, to sustain the basic life-supporting function of the environment, is the guiding principle for achieving agricultural sustainability. It is believed that nature imposes physical limits on the capacity to grow food. This is because there are finite supplies of natural resources and the environment has a limited capacity to absorb wastes (Douglass, 1984). Hence, impacts beyond the environment's assimilative capacity cannot be sustained.

Environmental degradation has implications on the resilience of ecosystems (Moffatt et al., 2001). Resilience is described as the magnitude of impacts that can be sustained by the environment before it is irreversibly degraded (Holling, 1973, 1986). The Earth has a limited capacity to assimilate shocks and cope with the negative environmental impacts associated with natural and man-made processes (Common & Perrings, 1992). In the predominantly environment-oriented perspective, it is believed that once this capacity is breached, system structure irreversibly flips to another state, such that the environment may be irreversibly degraded. This might have catastrophic and often unknown consequences on the very survival of human enterprise on Earth.

Protection of the environment is essential for the resilience of the system (Holland, 2003). Reduced biodiversity, impacts on ecosystems through wastes and pollutants, and climate change are some of the factors that lower the resilience of the environment (Folke et al., 2004). Hence, proponents of agricultural sustainability, based on the predominantly environment-oriented perspective, believe that agricultural practices should enhance the resilience of the environment. This may mean working compatibly with natural cycles, maintaining and promoting agrobiodiversity, closing the material cycles by recycling the outputs and maintaining harmonious relationships between plants, land and livestock (Milestad & Darnhofer, 2003).

In summary, although sustainability is described in terms of maintaining economic, social and environmental conditions, the interpretations of agricultural sustainability are varied. Worldviews play an important role in decisions about how much emphasis is given to the economic, social and environmental factors, in order to achieve agricultural sustainability.

2.3 Worldviews of sustainability

One of the ways to understand sustainability is based on capital theory. Capital is the “stock that yields a flow of valuable goods or services into the future” (Costanza & Daly, 1992, p. 38). In order to be sustainable, the total stock of capital that one generation passes on to the next has to be maintained or enhanced (Victor, 1991). The capital stock is composed of the economy (manufactured and financial capital), the society (social and human capital) and the environment (natural capital).

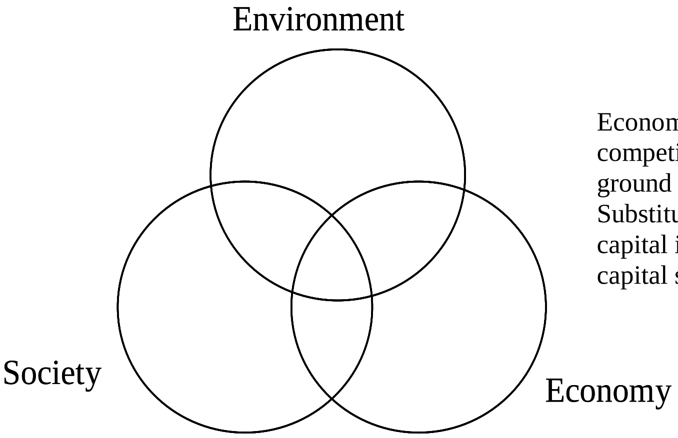
Two distinct worldviews exist, depending upon the extent to which different types of capital are believed to be substitutable for one another. These are the weak and strong concepts of sustainability. Weak sustainability allows for the near complete substitution of natural capital with other kinds of capital, whilst strong sustainability means no (or limited) substitution of natural capital with other kinds of capital (Neumayer, 2004). Weak and strong sustainability can be perceived as the end points of the continuum of sustainable development. Many sustainability proponents might find themselves somewhere in the middle of this continuum (Cutter & Renwick, 2004).

2.3.1 Weak sustainability

Under weak sustainability (WS), no special treatment is given to the maintenance of the environment (natural capital): the environment is simply considered as another form of capital (Pearce & Turner, 1990). In WS, it is assumed that the forms of capital are completely substitutable for each other. As a result, it is believed that degradation of one or more of the capital stocks (economy, society or the environment) can be compensated for by improvements in one or more of the remaining capital stocks, and thereby the total capital stock can be maintained (Gowdy & O' Hara, 1997) (Figure 2.1). In other words, it is possible to accept higher levels of degradation of the land resource and still retain the same ability to produce in the future, by investing in more R&D. This can be achieved by enhancing human capital through technological and productivity improvements and by increasing the knowledge embodied in land conserving practices (Stoneham et al., 2003).

In WS, it is acceptable to leave back less environmental assets to future generations, insofar as their loss is compensated for by increasing man-made capital, such as roads and machinery. Alternatively, fewer roads or other man-made items can be passed on to future generations insofar as more wetlands or meadows or education are left behind for future generations (Pearce, 1993). Since a nearly complete substitution between different kinds of capital is assumed, WS is often referred to as 'substitutability paradigm' (Neumayer, 2004).

In WS, the main priority is the health of the economy: it is assumed that social and environmental constraints can always be overcome, if the economy is sound (Gowdy & O' Hara, 1997; PCE, 2002). As WS is based on economic strategies, it is referred to as an 'econocentric concept'. In WS, environmental resources and their degradation are considered in monetary terms (Wiggering & Rennings, 1997).



Economy society and environment are competing and there is some common ground where each circle overlaps. Substitution amongst the different forms of capital is allowed insofar as the total capital stock is maintained or enhanced.

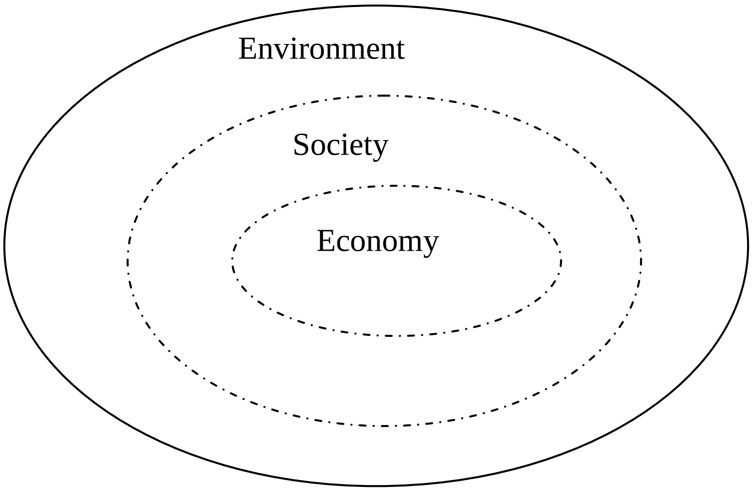
Figure 2.1 Model of Weak sustainability

2.3.2 Strong sustainability

The concrete point of difference between weak and strong sustainability is the non-substitutability or limited substitutability of natural capital with other forms of capital (Daly, 1991; Ekins, 2003; Neumayer, 2004). In strong sustainability (SS), natural capital must be protected separately, in addition to maintaining the total stock of capital. Therefore, a minimum necessary condition for strong sustainability is the maintenance of the natural capital stock at or above current levels (Daly, 1991; Costanza & Daly, 1992; Gowdy & O' Hara, 1997). Hence, strong sustainability is often referred to as the 'non-substitutability paradigm' (Neumayer, 2004).

In SS, the economy is a subset of the society, which itself is a subset of the physically finite environment (Figure 2.2). Human society and its socio-economic activities are ultimately constrained by the finiteness of the environment and therefore, environmental sustainability is considered as a prerequisite for socio-economic sustainability (Goodland, 1995; Goodland & Daly, 1996; PCE, 2002). This is true because, firstly, economy is not independent of natural capital. All economic processes require a continuous source of resources and a sink for wastes, both of which are provided by the environment. Secondly, natural capital provides other ecological services, including basic life support on Earth, of which humans are a part (Robert, 1997; Chiesura & de Groot, 2003; Ekins et al., 2003; Millennium Ecosystem Assessment, 2005).

Conserving natural capital, in general, is essential for sustainability because any degradation in natural capital may have uncertain and perhaps irreversible consequences for the existence of life on Earth (Pearce, 1993). There is extensive uncertainty about the way in which natural capital stocks work. The full working of ecosystems is not completely understood. This is the reason science has exercised great caution before labelling any form of natural capital as redundant. Similarly, it is not always possible to recreate natural capital stocks once they are lost. This is the problem of irreversibility: once lost, such assets might be lost forever (Pearce, 1993). The environment is a physical thing and its maintenance in physical terms is, therefore, essential for strong sustainability (Robert, 1997).



Economy and society are within the domain of the environment. Socio-economic considerations are ultimately constrained by the finiteness of the environment. Substitution between natural and other capitals is limited.

Figure 2.2 Model of Strong sustainability

2.4 Thermodynamics and sustainability

Underpinning strong sustainability are the laws of thermodynamics. All energy and matter in the universe are subject to the laws of thermodynamics, which are the physical laws that explain the conversion of energy and matter from one form to another and the subsequent impacts on the environment. The whole physical world around us is energy: both dead objects as well as living organisms that represent matter (Norde, 1997). This is because each object contains a certain amount of embodied energy, as per Einstein's equation $E=mc^2$.

The insights from thermodynamics have implications for sustainability because all processes on Earth (both natural and man-made) involve one form of energy being converted into another, with subsequent changes in the state of the environment. For example, radiation from the sun is transformed into heat at the Earth's surface, into chemical energy (via photosynthesis) in plants, into the latent heat of vaporisation when water evaporates and as long wave radiation reflected back into space (Peet, 1992).

The thermodynamic principles, most important for sustainability, are the first and the second laws. According to the first law, energy cannot be created or destroyed, only altered in form. This law is also called the energy-matter conservation law. For example, if all forms of energy entering a process and all forms of energy coming out are accounted for, the input and output will be equal. The first law, therefore, deals with the quantity of energy, without any regard to its quality (Sollner, 1997; Dincer et al., 2005).

According to the second law of thermodynamics, the usefulness of energy-matter decreases during each step of energy conversion, with a simultaneous increase of entropy[1]. According to the second law of thermodynamics, ordered energy from low entropy resources, such as fossil fuels and minerals, is transformed during resource use and is eventually dispersed into the environment in the form of high entropy substances, such as greenhouse gases, toxic substances etc. (Peet, 1992; Dincer & Rosen, 1998). Pollution and wastes (high entropy substances) are inevitable, due to the second law of thermodynamics (Georgescu-Roegen, 1971). "Waste is an output just as unavoidable as input of natural resources" (Georgescu-Roegen, 1976, pp 13). Therefore, the second law of thermodynamics has implications for environmental degradation.

The balance between the decreases in entropy and increases in entropy has implications for the degradation of the environment and thus, sustainability (Addiscott, 1995; Robert, 1997). Photosynthesis is the only large-scale energy conversion process that decreases entropy (Addiscott, 1995; Robert, 1997). During the process of photosynthesis, the green plant cell uses energy from the sun to convert small dispersed molecules (high entropy materials), such as CO_2, to more ordered substances, such as carbohydrates (low entropy materials). In nature, matter is transformed in the form of low entropy materials and partially in the form of high entropy materials. Photosynthesis, plant growth, formation of humus and development of soil structure, are processes that decreases entropy, whilst

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[1] Entropy is the degree of disorder which has implications for environmental degradation. It is the unavailable energy.

respiration, senescence, decomposition of humus, disaggregation, and breakdown of soil structure are processes that increases entropy (Addiscott, 1995).

Increases in entropy had kept pace with decreases in entropy in pre-industrial society (Robert, 1997). Pre-industrial societies used energy matter resources mainly from the ecosphere[2] and released wastes to the ecosphere, where they were converted into useful resources through photosynthesis and growth. The main cause of environmental degradation in industrial society, in recent times, is due to the increased use of substances from the lithosphere[3] and increased manipulation of the ecosphere, which increases pollution. Examples of environmental degradation include the greenhouse effect, ozone depletion and environmental pollution, such as chemical contamination, leaching and soil degradation (Norde, 1997). Environmental degradation occurs because:

1. Energy and matter, especially from non-renewable resources are used at a higher rate than the rate at which the wastes associated with them are assimilated by the environment; and
2. The resilience of the environment to assimilate wastes has been reduced because of loss of biodiversity, encroachment on wetlands, increase in desertification, emissions of CO_2, eutrophication and deforestation (Robert, 1997; Folke et al., 2004).

Both the first and second laws of thermodynamics have implications for sustainability. Without the first law, the second would be irrelevant, since energy could be created anew. Without the second law, energy could be used over and over again without environmental impact (Sollner, 1997). Thus, the sustainability of any economic system, such as agriculture, is constrained by the ability of the environment to provide energy and matter resources and the capacity of the environment to assimilate negative impacts from resource use. Sustainability, based

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[2] Ecosphere: that part of the Earth which contains the biosphere, the atmosphere (including stratosphere that contains ozone layer), and the pedosphere (layer of soil above the bed rock).

[3] Lithosphere is the outer solid part of the Earth that contains the crust and the mantle.

on thermodynamics, is constrained by energy and material flows and their impacts on the environment (Ruth, 1993).

2.4.1 Energy and material flows

Economic growth is dependent on sources of energy and matter, especially those derived from non-renewable resources such as fossil fuels, which are finite. The implication of this is that energy and matter resources derived from fossil fuels limit the ability to obtain output in any production process. This has led to the concept of energy as the ultimate limiting factor, because energy is the only commodity for which a substitute cannot be found and also because energy cannot be recycled due to the second law of thermodynamics (Gilliland, 1975).

The role of energy in the economic system is studied through energy analysis, the aim of which is to quantify the energy flows inherent in the economic process under consideration. The results of energy analysis is a measure of energy efficiency: energy efficiency within thermodynamics is based on the same formulation (Jollands, 2006):

$$\text{Energy efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \qquad 2.1$$

Energy efficiency can be estimated, based on either the first law or the second law of thermodynamics (Sollner, 1997). In practice, energy efficiency based on the first law of thermodynamics dominates because second law efficiencies, which are based on entropy, are difficult to calculate and the result does not markedly differ from energy efficiency based on the first law of thermodynamics (Sollner, 1997; Dincer et al., 2005).

Although energy plays a vital role in sustainability, energy analysis based on energy efficiency (energy output/energy input) cannot be the sole criterion for sustainability. This is because energy analysis has its limitations. In energy analysis, associated environmental degradation is not considered. This means that, in processes which are gauged on first law energy efficiency alone, no consideration is given to simultaneous environmental impacts such as greenhouse gas emissions, effects on biodiversity or leaching of nutrients to groundwater. Also, in energy analysis, the assimilative capacity of the environment to cope with negative environmental impacts is not considered (Brown & Herendeen, 1996; Fakhrul Islam et al., 2003). Hence it is important to discuss the transformation of matter which takes place under the implication of the second law of thermodynamics.

Energy and material flows are fundamentally interrelated and many of the material resources such as fossil fuels, are actually carriers of energy (Svensson et al., 2006). The material balance approach leads to the important insight that energy inputs and wastes outputs are related. It emphasises the fact that pollutants cannot be eliminated, when energy and matter that are especially derived from non-renewable resources are used. This is because 100% conversion is not possible under the second law of thermodynamics (Georgescu-Roegen, 1981).

The material flows studied through the material balance approach help to identify the wastes associated with energy use, that threatens environmental integrity (Neumayer, 2004). The increased use of resources by industrial society implies that resources are depleted, undesirable substances are accumulated, (such as toxic chemicals and pollutants) and the productive capacity of the ecosphere is deteriorated. As a result, the resilience of the environment to cope with negative environmental impact is lowered (Folke et al., 2004). A material balance approach is a useful way to identify the fate of material, from the time it was extracted, through its processing and manufacturing, to its ultimate disposition. The equation for material balance is expressed as:

$$Input = output + accumulation \qquad 2.2$$

2.4.2 Impacts on the environment

Energy and material flows, especially those derived from non-renewable resources, have important implications for environmental impacts. This is because with every stage of energy and matter conversion, entropy is produced, due to the second law of thermodynamics. Hence, environmental degradation has been considered as a proxy of entropy generation and as a measure of sustainability (Steinborn & Svirezhev, 2000; Svirezhev, 2000). Wastes associated with energy and material flows might cause environmental damage, due to the generation of pollutants and toxins released into aquatic systems and emissions of greenhouse gases (Rosen & Dincer, 1997, 2001). Other environmental issues, that are related to energy and matter use, are ozone depletion, radiation and radioactivity and hazardous pollutants in air, water and land.

Reducing the use of energy and material flows derived from fossil fuels, within agricultural systems, has important implications for the health of the environment and therefore sustainability (Edwards-Jones & Howells, 2001; Raman, 2006). Low fossil input agriculture is more sustainable than high fossil input agriculture for two reasons: firstly, because the higher the fossil input, the higher the rate of entropy generation and subsequent environmental impact (Ruth, 1993; Dincer, 2003) and secondly, energy from non-renewable resources is a scarce resource and will be exhausted at some point in time. Obviously, a system which depends on fossil energy input to a lesser extent is more sustainable than a system which uses a higher fossil energy input.

The efficient use of energy and material resources implies that human activities should close material cycles by recycling waste products, as far as possible, rather than simply dispersing or exporting these substances into the environment (Ruth, 1993). The environment has some capacity to recycle a part of these wastes back into useful resources, depending upon the environment’s assimilative capacity (Kim, 2004). As long as the wastes are assimilated, the human system will function like a natural system and it will have minimal negative impacts on the environment.

Sustainable systems therefore are ‘circular’, in which most of the outputs become inputs and as far as possible the wastes that are released into the environment are recycled (Hanson, 1997; Kim, 2004). For example, the burning of fossil fuel releases CO_2 into the atmosphere and efforts should be directed to capture the released CO_2 through long-term storage in biomass, and through photosynthesis, in order to recycle at least a part of the emissions and reduce the negative impacts.

2.4.3 Systems and thermodynamics

The definition of the system and its boundaries, and the evaluation of matter and energy flows across these boundaries, is essential in sustainability assessment (Ruth, 1993). A system is usually a group of interacting, interdependent parts linked together by complex exchanges of energy, matter and information (Costanza & Wainger, 1993).

Boundaries are necessary, in order to decide what factors are to be considered external and internal to the system. Therefore, the results of any system analysis depend on the definition of the boundaries of the system (Weston & Ruth, 1997; Dalgaard et al., 2001; Blanke & Burdick, 2005). Closed systems exchange only energy, not matter, with their environment. Earth is a closed system, since the only inflow is solar energy and only heat is radiated to outer space. Open systems are open to their environment, in a physical (thermodynamic) sense. They receive from and release to the environment, inputs and outputs of energy and matter. All systems on Earth, including farms, are open systems, through which materials and energy continuously flow into the natural environment (Addiscott, 1995; Svirezhev, 2000).

According to the second law of thermodynamics, the entropy of a closed system always increases (Bertalanffy, 1950). However, in open systems, entropy may increase, decrease or remain in a steady-state. A reduction in entropy is possible only because open systems on Earth become more ordered, but at the cost of environmental degradation (Giampietro et al., 1992; Ruth, 1993; Svirezhev, 2000; Miller, 2003). This implies that a farm, when considered as an open system, can be sustainable, at the cost of environmental degradation. However, open systems, such as a farm, are just a part of the biosphere as a whole and therefore they cannot be isolated from the closed system of the Earth. Therefore, any degradation in the natural environment will make a farm less sustainable. Hence, a farm should be considered together with the environment with which the farm interacts, to better account for environmental impacts, which in turn have implications on sustainability (Svirezhev, 2000; Wood et al., 2006).

2.4.4 Worldviews and thermodynamics

Strong sustainability (SS) is an appropriate worldview for achieving long-run sustainability (Munda, 1997; PCE, 2002; Stoneham et al., 2003). Based on thermodynamics, it is clear that environmental degradation has implications for sustainability. In strong sustainability, it is acknowledged that absolute scarcity of resources is imminent, in terms of the implications of the second law of thermodynamics and therefore only a limited trade-off with natural capital is allowed (Sahu & Nayak, 1994). Maintenance of natural capital is logical because sustainability of the economic system depends on the source-and-sink functions of the environment. The environment absorbs and purifies wastes/residuals produced by the economy and similarly the physical growth of the economic system depends on the source of continuous flow of energy-matter into the system from the biosphere. As Daly (1994a) argued, economic growth can occur only at the expense of the environment and an increase in the physical dimensions of the economy correspondingly decreases the physical size of the environment, since Earth has only a finite mass. This means environmental sustainability is a prerequisite for other types of sustainability.

The case for strong sustainability, as an appropriate worldview for sustainability, is also justified by the fact that it is based on the precautionary-principle[4] to preserve natural capital. Since there is uncertainty and irreversibility associated with the degradation of the natural capital, non-degradation of natural capital is especially important to sustainability of all human activities on Earth.

2.4.5 Theoretical principles for strong sustainability

The laws of thermodynamics provide a theoretical foundation for sustainability. Energy and material flows are the driving forces for changing the state of the environment. Knowing how material and energy flows are related to a particular

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[4] Precautionary principle means caution taken in advance. Precautionary principle is usually followed when there is uncertainty associated with the effects of a particular activity in terms of the impacts on the environment.

activity, such as agriculture, enables a realistic analysis of the interactions between economic activity and the state of the environment (Ruth, 1993).

The sustainability, or permanence of any activity is primarily a matter of resource availability and the waste assimilation capacity of the environment (Holmberg et al., 1996; Robert, 1997; Sollner, 1997; Adams, 2006). Given the fact that the environment has a limited capacity to provide resources and assimilate negative impacts, management practices should be based on the reduction in anthropogenic material and energy flows, especially derived from non-renewable sources, in order to achieve sustainability (Hinterberger et al., 1997; Neumayer, 2004).

However, absolute preservation of non-renewable resources is not realistic and needs to be replaced by acceptable levels of compromise (Turner et al., 1994; Raman, 2006). This is because firstly, human economic systems are very much dependent on primary resources and secondly, humans are a part of nature and therefore they interact with nature through energy and material flows. Also, non-renewable resources (fossil fuels and minerals) are used in less proportions by life forms other than humans and so extracting them can be considered irrelevant to the biosphere, insofar as the environment is not compromised (Haberl et al., 2004). Thus, sustainability, based on thermodynamic sense, implies that energy resources should be used efficiently and the impacts arising from energy and matter use should not degrade the environment (Ruth, 1993; Scheraga, 1994; Robert, 1997; Haberl et al., 2004). Towards this end, the following principles are proposed for sustainability (Daly, 1990):

1. Harvest rates for renewable resources should not exceed their regeneration rates;
2. Non-renewable resources can be exploited, but at a rate less than or equal to the creation of renewable substitutes; and
3. Waste generation from both renewable and non-renewable resources should not exceed the assimilative capacity of the environment.

Once these principles are achieved, traditional socio-economic criteria can be applied and the project or management option, which has the highest return in monetary terms, can be selected (Daly, 1991). Thus, a hierarchy is conceptualised in which sustainability based on thermodynamic interpretations is given the highest priority, followed by socio-economic concerns.

Sustainability based on thermodynamic interpretations, however, does not account for environmental impacts that occur as degradation in ecosystem services or biodiversity losses (Gudmundsson & Hojer, 1996; Svensson et al., 2006). The importance of ecosystem services and biodiversity has been widely acknowledged, since the Rio Earth summit held in 1992 (Millennium Ecosystem Assessment, 2005). Preserving biodiversity, by mitigating the loss of species and maintaining ecosystem services and genetic diversity, are therefore added as a fourth principle for sustainability, which complements Daly’s principles (Azar et al., 1996; Gudmundsson & Hojer, 1996; PCE, 2002).

2.5 Summary

It is clear that agricultural sustainability is a complex issue and it is difficult to evaluate because of ambiguities surrounding its meaning. The various worldviews associated with agricultural sustainability boil down to the relative importance of three basic concepts: environmental integrity, economic viability and social acceptability. Environmental sustainability cannot be compromised, since it is a prerequisite for other kinds of sustainability. Strong sustainability is based on thermodynamics insights and gives utmost priority to environmental sustainability. Strong sustainability is the appropriate view of sustainability, in order to achieve sustainable outcomes.

Farming systems are thermodynamically open systems, which constantly interact with the environment through the use of energy and materials across the boundary. However, the use of energy and materials degrade the environment, thereby ultimately reducing the environment’s ability to provide resources and assimilate negative impacts. Sustainability, in the context of limited energy resources and the limited assimilative capacity of the environment, implies that energy use should be efficient and the negative impacts associated with energy and material use should not degrade the environment. Efficient energy use is based on the first law of thermodynamics, whilst environmental impact from energy and material use is based on the second law of thermodynamics. Thus, agricultural sustainability for this research implies the following:

1. Environmental sustainability is given the highest priority at the farm level, followed by socio-economic concerns. Although socio-economic concerns are important for sustainability, they are ultimately constrained by the natural environment and therefore they are important, once the environmental criteria are achieved; and
2. A farm is merely a part of the natural environment in which it is embedded and hence farming system sustainability must consider the environment with which the farm interacts. Sustainability at the farm level is studied from the energy and material flows and the environmental impacts associated with them across the farm and the environment.

Chapter 3

AGRICULTURAL SUSTAINABILITY ASSESSMENT

3.1 Introduction

In the previous chapter, the implications of thermodynamics for sustainability were explained and the theoretical principles for sustainability presented. In this chapter, different approaches to sustainability assessment are reviewed, in order to determine which ones, if any, are appropriate for this research. Also, issues surrounding agriculture and associated environmental impacts are reviewed, in order to identify the key agri-environmental indicators relevant for organic orchard systems. Building on this literature, and the literature in Chapter 2, an analytical approach for sustainability assessment at the orchard systems level is proposed.

3.2 Approaches to sustainability assessment

In order to make progress towards sustainability, formal assessment of sustainability is essential (Rao & Rogers, 2006). To gauge progress, sustainability assessment should guide decision-making and policy development, raise social awareness and understanding and increase public participation (United Nations, 1992).

Since sustainability first became prominent in international discussions, numerous approaches to its assessment have been developed. These approaches are continually evolving. For the purposes of this research, it is important to know whether the approaches for sustainability assessment are based on: 1) temporal characteristics – sustainability essentially has a time dimension and it is important to know what temporal aspect is covered by a particular sustainability assessment approach; 2) spatial characteristics – whether the sustainability assessment approach is useful at the farming system level; and 3) whether the approach is based on thermodynamic interpretations of sustainability.

Three categories of approaches can be identified for sustainability assessment based on the temporal focus, which is either retrospective (assess sustainability after the fact, looking back in time), prospective (forward looking, forecasting) or both. These approaches are: indicators/indices, which mainly have a retrospective focus; product related assessment, which can have both retrospective and prospective focus; and integrated assessment, which usually have a prospective focus (Ness et al., 2007). These are described below.

3.2.1 Indicators and indices approaches to sustainability assessment

Indicators are the primary vehicles for measurement of sustainability. They can be effective tools in the operationalisation of agricultural sustainability (Rigby et al., 2001). Indicators are simple measures that represent status, performance and trends of the system under investigation (Becker, 1997; Ness et al., 2007). A good indicator for sustainability assessment should have the characteristics of simplicity, a wide scope, be quantifiable, be sensitive to change and it should allow timely identification of trends from a retrospective perspective (Harger & Meyer, 1996; Ness et al., 2007). Also, an important role of a sustainability indicator is to raise awareness of a resource management issue, which should lead to a change in management (Pannell, 2003). In this way, sustainability indicators should be able to guide management to move a system toward a more sustainable state.

Indicators can either be non-integrated or integrated. When different indicators are kept separate they are called non-integrated and when different indicators are aggregated in some manner into an index they are called integrated (Ness et al., 2007).

3.2.1.1 Non-integrated indicators

The Pressure-State-Response (PSR) framework devised by the OECD is one approach by means of which indicators for agri-environmental impacts can be identified (Rao & Rogers, 2006). In the PSR framework, three types of indicators are identified: pressure indicators that describe pressures from human activities exerted on the environment; state indicators that assess environmental conditions;

and response indicators that show the extent to which society is responding to environmental changes and concerns.

The FAO, World Bank and others have used the PSR framework, or some variation of it, to develop environmental and sustainable development indicators (Pieri et al., 1995; FAO, 1997). For example, the LQI (Land Quality Indicators) programme developed in collaboration with the World Bank and FAO, UNDP (United Nations Development Program), UNEP (United Nations' Environment Program) and the CGIAR (Consultative Group on International Agricultural Research) are based on the PSR framework (Dumanski & Pieri, 2000). The LQIs can be applied at different scales, such as farm, local, district, national and international (Pieri et al., 1995). The LQIs include pressure indicators such as cultivated area/arable area, yield/arable land, soil conserving/soil degrading crops and nutrient inputs/nutrient export. The state LQIs are identified as soil nutrient balance, land cover, changes in the soils' physical and chemical properties, agro-biodiversity, water quality, land contamination/pollution and forest and rangeland quality (Dumanski & Pieri, 2000). The response LQIs include legislation for conservation, activities, size and membership in conservation associations (Pieri et al., 1995).

The FESLM (Framework for the Evaluation of Sustainable Land Management) was developed through collaboration amongst international and national institutions under the auspices of the FAO, in order to assess the sustainability of land management based on indicators (Smyth & Dumanski, 1993). Land management under this framework is deemed to be sustainable if the following pillars are addressed simultaneously:

- Productivity – maintaining or increasing the production.
- Security – reducing the level of risk.
- Protection – enhancing environmental (land) quality.
- Viability – being economically viable.
- Acceptability – being socially acceptable.

The FESLM has been used to study land management for the development of decision support systems in Canada, Vietnam, Thailand, USA and Nepal (Lescourret et al., 1999; Gameda et al., 2006; Rais et al., 2006). In an example based on FESLM, data were collected through farmer surveys in Vietnam, Indonesia and Thailand, in order to develop sustainable land management (SLM) indicators for each of the five pillars of sustainability. Based on the collected data from the case studies, the indicators and the threshold[5] values were decided by the farmers, in collaboration with the researchers. A decision support system was developed to assess the status of each of the five pillars, using responses to the questions, based on the respective indicators. The answers to each question were characterised as having a weighted impact on the particular pillar to which they were associated. Summations of the various indicators gave a score between 0 and 1 for each pillar. The overall sustainability of the system was then assessed on the status of the least sustainable pillar. The limitation of this approach was that each indicator was assumed to be independent of other indicators and influenced only one of the five pillars of sustainability. Examples of some of the indicators under each pillar of the FESLM are (Lefroy et al., 2000):

- Productivity – yield, soil colour, plant growth, leaf growth.
- Security – average annual rainfall, residue management, drought frequency, income from livestock.
- Protection – topsoil erosion, cropping intensity, cropping pattern.
- Viability – net farm income, off-farm income, difference between market price and farm price, availability of farm labour, land holding size, availability of farm credit.
- Acceptability – access to extension services, primary schools, health centres, agricultural inputs and roads.

Based on FESLM, Gomez et al., (1996) assessed sustainability at the farm level, based on easily measurable indicators. Information was collected from the growers to estimate indicators falling under the groups of ‘farmer satisfaction’ and ‘resource

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[5] A threshold is the level beyond which a system undergoes significant change.

conservation'. The indicators under the group farmer satisfaction included yield, profit, and crop failure, whilst those under resource conservation included soil depth, organic carbon and ground cover. A trade-off was allowed amongst indicators within the same group, but not between groups. Thus, environmental aspects were not traded-off with economic aspects and it was required that environmental aspects, in addition to socio-economic aspects had to be maintained separately, in order to achieve sustainability. The thresholds in the study were set in consultation with the farmers. The indices for farmer satisfaction and resource conservation were computed as the average of the three indicators under each of these groups, respectively. The indices for farmer satisfaction and resource conservation must both be greater than 1.0 for the system to be judged sustainable. An average of these two indices finally gave the value for the overall index for sustainability of the agroecosystem. Although the indicators were aggregated into a single index, no information was lost, since individual indicators could be tracked back. However, in the analysis, the off-farm environmental impacts of farming were not considered, since the system boundary was considered to be the farm's physical boundary and outputs leaving the farm system were not taken into account.

Although several indicators are useful to obtain a broad picture of sustainability, as followed in the approaches reviewed above, data collection for all indicators is a time consuming process. Whilst there is no rule on the exact number of indicators used in sustainability assessment, experience has shown that long lists of indicators are impractical (Lopez-Ridaura et al., 2005). It is therefore argued that fewer indicators send a clearer message to policy makers (Sikdar, 2003). The use of energy, especially derived from non-renewable resources, is an important indicator for sustainability, because it is finite and its use almost certainly leads to environmental impacts.

Energy analysis is one of the approaches based on thermodynamics, for assessing sustainability of agricultural systems. Energy analysis is the process of determining the energy required directly and indirectly to allow a system (usually a socio-economic system) to produce a specified good or service (IFIAS, 1974 cited in

Brown and Herendeen, 1996). Energy analysis provides indication for the total energy use of a farming system. This technique requires quantifying the energy equivalents for the most significant energy and material flows associated with agroecosystems. In this manner, all inputs are expressed in one general unit – energy. This makes it possible to compare different energy flows and to calculate the ratio of outputs of agricultural production to inputs of cultural energy[6]. Agricultural systems are considered energy efficient if the energy output to input ratio is greater than one (Schroll, 1994; Fakhrul Islam et al., 2003). The ratio of energy output to cultural energy input can be greater than one: this is possible because solar energy is excluded from energy analysis (Stout, 1990; Steinborn & Svirezhev, 2000). In this way, the energy ratio, in the form of first law energy efficiency, has been used in agriculture as an indicator of sustainability (Pimentel et al., 1983; Schroll, 1994; Reganold et al., 2001; Fakhrul Islam et al., 2003). However, as described in Chapter 2, energy analysis does not consider associated environmental impacts, nor does it consider the role of environment in coping with negative environmental impacts.

In order to overcome this limitation of energy analysis, an estimation of overproduction of entropy has been used as an approach to assess sustainability at the agroecosystem level (Steinborn & Svirezhev, 2000; Eulenstein et al., 2003). This approach is based on the assumption that energy analysis, as proposed by Pimentel (1973), is insufficient because it does not quantify the associated degradation of the environment, as a result of energy and matter use. Entropy overproduction is based on the second law of thermodynamics and therefore entropy is used as an indicator for environmental degradation (Eulenstein et al., 2003). Environmental degradation is accounted for through the estimation of overproduction of entropy, as compared to a reference point which is an undisturbed natural ecosystem. The balance of entropy is the difference between production and export of entropy. An entropy balance of greater than zero means that there was entropy overproduction, which is equivalent to negative impacts on

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[6] Cultural energy is the energy supplied through the agency of man. It includes inputs derived from non-renewable resources, such as fossil fuels or renewable resources of energy, such as human and animal labour (Heichel, 1974).

the environment. However, an important limitation to this approach is that, although it allows for the evaluation of environmental degradation in general, the exact areas where degradation occurs and in what form cannot be predicted (Eulenstein et al., 2003). It is not possible to point out whether the environmental degradation occurs as soil erosion, a change in pH, an impact on biodiversity, greenhouse gas emissions, deterioration in water quality, or some other processes. The other limitation of this analysis is the requirement of a large amount of empirical and statistical data.

Emergy has been referred to as energy 'memory' (Scienceman, 1989, cited in Brown and Herendeen, 1996). Emergy analysis is a technique of quantitative analysis to determine the values of system components in common units of solar energy used to make them (called solar emergy). The basis of emergy analysis is the conversion of all processes into solar energy, by a conversion factor called solar transformity. Solar transformity is defined as the solar energy directly or indirectly necessary to obtain one unit of another type of energy. When a system is evaluated in solar emergy, the quantities represented are the memory of the solar energy used to make it. As a result, the quantities are not energy and do not behave like energy (Brown & Herendeen, 1996). Emergy analysis has been used as a method to evaluate efficiency and overall sustainability of agricultural systems (Bastianoni et al., 2001). In agricultural systems, the emergy yield ratio is the ratio of the emergy of a product to the emergy of the inputs (Martin et al., 2006). The higher the value of this index, the greater the return obtained per unit of emergy invested and more sustainable the system. The environmental loading ratio is the ratio of the total emergy of the non-renewable inputs, to the emergy of the environmental renewable inputs. The lower this ratio, the lower the stress to the environment (Bastianoni et al., 2001). Thus, results and conclusions of emergy analysis are obtained by the integration of the information given by all these parameters. Emergy analysis has been used to compare different agricultural systems in their resource use, productivity, environmental impact and overall sustainability. However, emergy analysis is criticised because of the difficulty in obtaining details about underlying computations for solar transformity and also because the uncertainties associated with them are not considered (Hau & Bakshi, 2004).

3.2.1.2 Integrated indicators

One of the ways to report on sustainability is by integrating individual sustainability indicators into a single index, in order to provide an overall picture of sustainability. Integration can bring a large set of indicators to one integrated index. A great deal of information is condensed into an index and therefore it is usually favoured by decision-makers (Malkina-Pykh, 2002).

Sands and Podmore (2000) developed and applied the environmental sustainability index (ESI), as an indicator to assess sustainability of agricultural systems and applied it to the farms in Colorado, USA. The most important contribution of this research is that it provided advice on how individual indicators could be integrated to provide an overall picture of sustainability. The ESI is based on 15 indicators, which cover aspects of soil properties, groundwater resources and off-site impacts. These indicators are weighted equally and then aggregated into a single index to give an overall value for environmental sustainability. As proposed by Sands and Podmore (2000), ESI reflects the degree of unsustainability of the system. When the ESI is zero, it corresponds to a condition of sustainability, whilst larger values indicate unsustainability. The ESI considers both on-site and off-site impacts for assessing the soil and water attributes of an agricultural system (Sands & Podmore, 2000).

There are other examples of integrated indicators, including The Index of Sustainable Economic Welfare (ISEW), The General Progress Indicator (GPI), The Adjusted Net Savings, The Ecological Footprint, The Wellbeing Index and The Human Development Index (HDI) (Ness, et al., 2007). However, these integrated indices are most commonly used at higher spatial levels than the farm level. Within these indices, specific environmental impacts can be calculated for a region within a country, or at the national level.

Aggregation of indicators into an index has also been criticised. Estimating sustainability with only one value has been criticised, because the index combines several disparate elements, thus making it less meaningful (Gomez et al., 1996; Sands & Podmore, 2000; ESI, 2005). The loss of information or the difficulty in tracking back individual indicators can lead to results that might be less useful or ambiguous (Rees & Wackernagel, 1996). Even if equal weight is given to each indicator, the component that has the highest number of indicators ends up weighted more heavily, than those consisting fewer indicators (Rao & Rogers, 2006). Another problem with single aggregated indicators is the lack of compensation between the values of its components. For example, low nitrogen leaching cannot balance increasing soil erosion.

3.2.2 Product-related approaches to sustainability assessment

The second approach to sustainability assessment focuses on flows associated with the production and consumption of goods and services (Ness et al., 2007). This approach allows both retrospective and prospective assessments of sustainability. The three approaches, which are based on product-related assessments, are described below.

3.2.2.1 Product-related life cycle assessment

The most widely used approach under the product-related approaches to sustainability assessment is the Life cycle assessment (LCA). LCA is used to evaluate resource use and environmental impacts along the production chain or through the life cycle of a product (Franklin, 1995; Canals et al., 2006). It is an approach that can be used to analyse real and potential pressure that a product exerts on the environment during raw material acquisition, production processes, product-use and product-disposal. The concept in LCA is to keep the entirety of the system in mind when considering the sustainability of certain components.

The LCA technique was introduced as an environmental management tool for industrial processes (ISO, 1998). However, increasingly, it has been adapted to study environmental burdens associated with agriculture (Audsley, 1997; Haas et al., 2001; Brentrup, 2003; Canals, 2003; Mouron et al., 2006). In various studies, LCA has been used to identify the environmental impacts related to a particular production system and to compare different systems in terms of their environmental impacts (Audsley, 1997).

In LCA, environmental impacts are usually categorised as depletion of abiotic resources (e.g., fossil fuels, phosphate rock and potash), land use, climate change, toxicity (human and ecosystems), acidification and eutrophication (Brentrup, 2003). Pollutant emissions which have a long-lasting effect (exceeding annual time periods), such as the effect of greenhouse gases, can also be accounted in LCA (Payraudeau & Hayo, 2005).

A traditional LCA is conducted in a number of phases. However, this is often time-consuming, laborious, expensive and data intensive (Mueller et al., 2004; Payraudeau & Hayo, 2005). A new trend is towards simplified LCAs, without the need to undertake a detailed LCA (Christiansen, 1997; ISO, 1998). Simplified LCAs cover the whole life cycle, but more superficially, for example by using generic data and by focusing only on the most important environmental impacts.

3.2.2.2 Product-related energy flow analysis

Product-related energy flows in LCA are also recognised for their relevance to sustainability assessment and policy development (Ness et al., 2007). Product-related energy includes both direct energy[7] and embodied energy. Embodied energy is the energy that is used in the production of the inputs, which in turn are used in producing the final product. Product energy analysis is the energy that is required to manufacture a product or a service, usually expressed in thermal equivalent of heat (MJ) (Herendeen, 2004). Energy use has been studied in product-related energy flows in agriculture and expressed as MJ/t of the output (Canals et al., 2006).

3.2.2.3 Product-related material flow analysis

In product material flows analysis, all the material flows connected to a particular product or a service are considered from a life cycle view. This enables discovery of where the inflows and outflows of substances occur and makes it possible to identify the source of the environmental impact and where environmental burdens can be reduced (Ness et al., 2007).

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[7] Direct energy is energy input used in production, which can be directly converted into energy units (Dalgaard et al., 2001).

3.2.3 Integrated assessment approaches

Integrated assessment approaches are usually based on systems approaches. The integrated assessment approach are usually useful for supporting decisions related to a policy or project implementation and are generally used as a forecasting tool (Ness et al., 2007). In the context of sustainability assessment, integrated assessment approaches are usually carried out in the form of scenarios analysis. The two approaches under this category are described below.

3.2.3.1 Modelling as an approach to sustainability assessment

Modelling, in the context of sustainability assessment, is an approach which allows us to learn where changes in the system can be made for increasing sustainability (Ness et al., 2007). In this way, modelling approaches are considered desirable in sustainability assessment, because they are prospective tools. Models enable managers, policy-makers and all those interested, to forecast the effect of a proposed change in the system in terms of impacts, benefits, risks or the factors that are most important to affect sustainability. Modelling can be particularly useful because experimentation with the actual system can be costly, time-consuming and may not be realistic in all situations (Robinson, 2006). This means that experimentation with model systems can be conducted cheaply and with more time efficiency than with the real systems.

In modelling a particular system for sustainability, firstly the qualitative relationships between different system components are conceptualised. This phase is often called conceptual modelling, mental modelling or soft systems modelling (Ness et al., 2007). Conceptual modelling forms the initial step in modelling the systems for sustainability analysis, since it is at this stage that the concept of sustainability and the various components of the system are qualitatively described.

To identify the environmental impacts of agriculture, a quantitative measure is required to relate the different components of the system, in order to estimate the sustainability indicators (Sands & Podmore, 2000). Modelling provides a way to integrate the various sustainability indicators in a systems approach (Malkina-Pykh, 2002). By relating indicators to each other in a systems perspective, models can help to analyse consequences of policies, to identify critical aspects of the system (that could be useful indicators), to understand the effect of a particular worldview and to put indicators in an interactive context (Rotmans & de Vries, 1997). In this way, the model predictions based on key indicators are useful to decision-makers for formulating appropriate policies.

However, similar to other approaches for sustainability assessment, the development of models for sustainability analysis is subjective. Models are developed, based on which components are considered to be important for the modeller (Ness et al., 2007). For example, how a modeller defines sustainability largely determines how a modeller goes about modelling a particular system. Thus, the decision of what to include in the model and what to leave out may have strong implications for the model results and their interpretation (Lotze-Campen, 2008).

At a spatial level, models which can be applied for sustainability assessment at the farming systems level are considered most appropriate for this research. There are several existing models used in the assessment of sustainability. Of these, biophysical models are important in environmental sustainability assessment. A biophysical model for sustainability assessment at the farming system level should be able to relate management practices to environmental impacts, in order to estimate sustainability indicators (Sands & Podmore, 2000). In this way, the effects of current management practices can be identified and improvements can be suggested to move towards more sustainable practices. The key biophysical models that can be applied at the farming system level are described below.

The Erosion/Productivity Impact Calculator (EPIC) is an example of a systems dynamic model, which is used to predict the long-term relationship between soil erosion and soil productivity (Williams, 1990). The EPIC model has been the most commonly used soil-process model developed to simulate the soil and crop components of the agricultural system. It is a widely used and tested model for simulating many agroecosystem processes, including plant growth, crop yield, tillage, wind and water erosion, runoff, soil density and leaching (Izaurralde et al., 2006). The EPIC provides detailed results but the input requirements are substantial, since it is a daily time step model.

FARMsim is another model that was developed as a farm management tool to identify the impact of new management strategies on the yield, nutrient cycling and resource flows at the farm level (Schaber, 1997). This model identifies the effect of different management strategies to minimise waste outputs and thereby increase efficiency of the whole farm. This model is an input-output model with various intermediate stages of converting external inputs into marketable outputs. The whole farm is compartmentalised into various farm enterprises (stocks), which are characterised by inputs and outputs. To be able to identify the major enterprises and their stocks and the flows of a typical farm, information is gathered through conversations with the farmers. In addition, information was gathered from scientists and researchers on (Schaber, 1997):

- The importance of certain stocks and their significance concerning the whole farm;
- Potential recycling flows;
- At what time of the season cultivation methods are carried through, e.g. land preparation, transplanting, harvest;
- Daily rates of certain flows, e.g. manure application to pond;
- Average growth rates of livestock; and
- Management strategies in general throughout a season.

Examples of enterprises in FARMsim include the stock of buffaloes, poultry, pigs, trees, fish in rice pond and rice. The change of the stock values, in relation to the quantity of in- and outflows, is then determined for each enterprise on the farm, using Stella® modelling software. Different enterprises were then integrated to create a model for the whole farm.

In FARMsim, efficiency is considered as an indicator of sustainability, which was estimated as the ratio of nitrogen in output to that in input brought from outside the farm. However, due to the lack of available data, the relationship between all identified enterprises and flows cannot be quantified. The model suggests that, in order to develop management strategies to improve sustainability of the whole farm, much more quantitative data are required, in order to improve the model.

Nutrient budgets are increasingly being recognised as an important tool in assessing the environmental impact and sustainability associated with agricultural management. One model that has been widely used in New Zealand, to determine the effect of nutrient use and their flows within a farm on nutrient-use-efficiency and possible environmental impacts, is the Overseer® nutrient budget (AgResearch, 2006). The environmental impacts are modelled as N and P losses to the water and as greenhouse gas emissions in terms of CO_2-equivalent emissions. The CO_2-equivalent emissions include the methane from animals, nitrous oxide emissions from the effluents, N fertilisers and other indirect sources, and CO_2 emissions from the use of fuel and capital. The model also predicts the nutrient balances for primary and secondary nutrients and therefore is important in nutrient management. The Overseer® model is improved and updated as new research or farm practices become available. This model has been constructed in consultation with end-user groups, and it has been specifically designed to only include parameters that the farmer knows or can readily obtain. The Overseer® model can be applied to pastoral, cropping, or horticultural systems.

3.2.3.2 Environmental impact assessment

Sustainability assessment has been increasingly associated with the environmental impact assessment tools, which take an integrated approach to sustainability assessment (Ness et al., 2007). Environmental impact assessment (EIA) is a standardised technique, developed in the 1970s, to identify the possible impact – positive or negative, that a proposed project may have on the natural environment. The purpose of the assessment is to ensure that decision-makers consider environmental impacts, before they decide whether to proceed with the project. In this way, EIA can be used as a forecasting tool to aid in the decision-making process, before any new policy comes to place. Unlike LCA, this approach is concerned mainly with assessing localised environmental impacts, rather than global impacts such as climate change from greenhouse gases (Lenzen et al., 2003; Payraudeau & Hayo, 2005).

EIA has been used at the farm level by the Food and Agriculture Organisation of the United Nations (FAO) to identify the environmental and socio-economic impacts of proposed agricultural development, with the aim of reducing the negative environmental impacts. It has been used to predict environmental impacts associated with the proposed irrigation projects, with the aim to mitigate negative impacts and enhance positive impacts (Dougherty & Hall, 1995). In a recent example, regulations based on an EIA analysis were developed to protect uncultivated and semi-natural areas from being damaged by agricultural work in England (Natural England, 2007).

3.2.4 Summary of sustainability assessment approaches

As discussed in Chapter 2, the sustainability assessment approach should: (1) be based on scientifically acceptable conceptions of the world, such as thermodynamics; (2) be defined by criteria, such as energy and material flows and their impacts on the environment; and (3) sustainability assessment should see the society and the economy as subsystems of the ecosystem at each scale, thus giving priority to environmental sustainability. The review of the various sustainability assessment approaches suggests that a practical approach to sustainability assessment should give a definitive answer about sustainability guided by threshold levels; provide information which is not lost through aggregation; and be relatively simple and easy to use.

The various sustainability assessment approaches reviewed above differ because of the fundamentally diverse assertions on which they are based (Haberl et al., 2004). As such, there is no universal and agreed upon best approach for sustainability assessment. This means that many approaches are only useful under some contexts. For example, retrospective tools are basically developed for analysing the past, although they can be sometimes used for assessing future patterns. Prospective tools are more favourable for sustainability assessment, since they can be useful to forecast future changes in the systems, by undertaking different scenarios analyses.

Although the energy analysis and the production of entropy in sustainability assessments are based on scientific laws, such as thermodynamics, they have their limitations. Energy analysis does not consider associated environmental impacts, whilst entropy-based analysis does not answer which components of the environment are degraded. Also, the spatial focus taken in the various sustainability assessment approaches differs. Many approaches do not consider the environmental impacts outside the farm’s physical boundary in sustainability assessment. However, sustainability assessment, based on thermodynamics, indicates that it is essential to consider the system-wide impacts. This means that environmental impacts outside the farm’s physical boundary should be considered within sustainability assessment.

From the criteria for sustainability identified in Chapter 2, the energy use should be efficient and energy and material use should not degrade the environment. To attain this goal, indicators are required that relate management practices to energy use and their environmental impacts. Management decisions at the farm affect the magnitude and type of resources, which have implications for environmental degradation and sustainability (Ruth, 1993). Therefore, in assessing sustainability at the farm level, it is necessary that the key environmental impacts from agriculture are clearly understood and appropriate indicators are identified.

3.3 Agri-environmental impacts and indicators

Environmental impacts from agricultural systems are at the heart of agricultural sustainability analysis. The issues of sustainable agriculture, the environment and natural resource use are high on both the domestic and international policy agendas. Interest in sustainability and public concern about environmental impacts of agricultural enterprises has stimulated governments to evaluate and monitor the state of the environment and detect changing conditions and trends.

Work on environmental impacts in agricultural sustainability assessment has been backed by significant national and international initiatives, together with work by individual scientists and research groups (Rao & Rogers, 2006). Progress has been made in developing common methodologies to measure agri-environmental performance, by identifying various environmental impacts and deriving appropriate indicators. An effective agri-environmental indicator is one that has policy relevance, is analytically sound, can be interpreted easily and is measurable (OECD, 1999). The key agri-environmental impacts and their indicators are described below.

3.3.1 Energy use

Combustion of fossil fuels contributes to their depletion, as the combusted resources cannot be reused. Therefore, the sustainability of agricultural systems depends on the extent to which these resources are used. Modern agriculture is an important user of non-renewable resources and therefore the energy flows in agriculture have become important for sustainability. Douglass (1984) stated, “to understand how energy affects the sustainability of agriculture is to understand all of agriculture” (p. 77). Agriculture converts solar energy and cultural energy input into food energy output (Heichel, 1973; Pimentel, 1980). The majority of the energy for primary plant growth and productivity is derived from the sun, which is a renewable resource and practically non-polluting (Pimentel, 1980; Adams, 2006; Raman, 2006). The remainder of the energy is sourced from mostly non-renewable resources (fossil energy) which are used in agriculture for preparing the land, irrigating, planting, transporting, processing, spraying, harvesting, fertilising and so on. In spite of the fact that most energy comes from the sun, it is possible that the fossil energy input is greater than the energy content of the food harvested (Pimentel, 1980). For example, in one study, organic and conventionally grown apples in the USA required higher cultural energy input than that which is being recovered as energy in fruits (Funt, 1980). This fact shows the extent of agriculture’s reliance on non-renewable resources.

As already described, energy efficiency in terms of energy ratio has been used as an indicator for energy use in agriculture. However, in addition to energy use and its associated indicators, other environmental impacts and their indicators must be considered for sustainability analysis. These are described below.

3.3.2 Impacts on soil

A healthy soil is considered crucial to sustainability. Soil has to be protected from degradation so that soil productivity is maintained or enhanced over time. Since soil is only slowly replaced, it is considered to be a non-renewable resource (Warren et al., 2001). The key soil impacts include soil erosion and degradation in soil quality. These impacts and their indicators are described below.

3.3.2.1 Soil erosion

Loss of soil is one of the important environmental impacts around the world (Oldeman, 1994; Millennium Ecosystem Assessment, 2005). Farm management practices can influence the rate of soil erosion. For example, use of cover crops, compost application, or reduced tillage has a positive effect in reducing the rate of soil erosion. Mechanical cultivation, clean cultivation (keeping the soil exposed without any vegetation cover) and overgrazing are some of factors that can increase soil erosion.

Soil conservation measures, sediment control measures, vegetation cover and the rate of soil formation have all been suggested as indicators of soil erosion (Gomez et al., 1996; Warren et al., 2001; Okoba & Sterk, 2006).

3.3.2.2 Soil quality

Soil quality has been described as the ability to sustain biological productivity, maintain environmental quality and promote plant and animal health (MAF, 1994a; Arshad & Martin, 2002). Soil quality is influenced through the loss of organic matter, soil fertility and soil structure. The factors which affect the soil quality and their indicators are described below.

Soil organic matter is an important factor that influences soil quality and it plays an important role in increasing productivity (OECD, 2001; USDA, 2003). Farm management can have a positive as well as negative effect on the soil organic matter content. Soil organic matter content is estimated from the percent of carbon. Cultivation causes oxidation of soil organic matter, and as a result the level of carbon in the soil declines, compared with undisturbed soils (Shepherd et al., 2003). Straw burning (a practice commonly followed in many places) reduces soil organic matter, whilst straw incorporation into the soil, maintenance of cover crop and the addition of manure increases organic matter and therefore the amount of carbon (Audsley, 1997). Thus, the soil carbon level is determined by the factors that influence the increase and decrease of carbon in the soil (Johnston, 1986). Carbon is sequestered in the soil when the carbon inputs through crop residues, compost and manures exceed the rate of carbon loss.

Soil fertility is another important factor that influences soil quality (FAO, 2005). The nutrient balance of the soil is an important indicator of soil fertility. This is estimated by comparing nutrient inputs with outputs. Inputs depend upon fertilisers applied and atmospheric inputs such as rainfall and nutrients released slowly from the soil (Condron et al., 2000). Outputs are determined by the amount of nutrients removed in products, loss of nutrients to water and atmospheric losses in gaseous form. Nutrient balances are usually considered for primary and secondary plant nutrients, such as N, P, K, Ca, Mg, and S. A negative nutrient balance suggests that the system relies on mining soil nutrient reserves, which in the long term is not sustainable. On the other hand, a large positive nutrient balance is of concern because it indicates that losses to the environment could potentially be large, with subsequent damage to the environment (Watson et al., 2002).

Soil structure also influences soil quality. Soil structure is indicated from bulk density or penetrometer resistance measurements and more recently, from soil resistance and conductivity surveys (Kerry & Oliver, 2007). Soil structure can also be indicated by physical parameters such as stability of aggregates, percentage of coarse pores, air capacity and soil water holding capacity. Soil organic matter content and management practices (no tillage, reduced tillage, ploughing, soil disturbance) also influences soil structure (Ministry for the Environment, 1997). For example, depletion of soil organic matter and soil compaction from heavy machinery traffic or grazing intensity can degrade soil structure (Stolze et al., 2000).

3.3.3 Impacts on water

There are numerous impacts of agriculture on water quality and these may occur as contamination by nutrients, lower amounts of dissolved oxygen, higher microbial count, changes in pH, changes in conductivity, faecal contaminants, suspended solids and increase in water temperature (OECD, 2001). However, the key impacts of utmost concern, regarding agriculture and water quality, are eutrophication and contamination of water by pesticides (OECD, 2001).

3.3.3.1 Eutrophication

Eutrophication is generally understood as an excess level of nutrients in water sources, which lead to changes in species composition in the ecosystem. In natural systems, the level of nutrients in water is in balance with the growth of the biomass (Pennington *et al.*, 2004) (exceptions occur when non-equilibrium conditions exist for a period of time following extreme disturbances, eg. flooding or fire). In a farming system, this balance is disturbed by material and energy flows that occur from fertiliser application, tillage and deforestation. Of particular concern are increases of N and P, which are the major plant nutrient responsible for eutrophication and related impacts on aquatic life and water quality (OECD, 2001). The levels of nitrogen and phosphorus in water bodies have been suggested as indicators of eutrophication.

3.3.3.2 Contamination of water by pesticides

Pesticides include insecticides, fungicides, herbicides, nematicides, rodenticides plant growth regulators, and any other chemicals which are used to control any pest. Contamination of water by pesticides can result from leaching through the soil profile, surface runoff, soil erosion, or direct application of pesticides close to surface waters. The movement of pesticides from soil to water depends on soil-type, rainfall, drainage flow path, temperature, pesticide application method, frequency of application, and the type of pesticide itself (OECD, 1999).

The magnitude of pesticide use and pesticide risk have been used as indicators of pesticide contamination (OECD, 2001). The magnitude of pesticide use is measured in tonne per hectare of active ingredients, whilst pesticide risk is the harm caused to humans and the environment by combining information on pesticide toxicity and the quantities of their use.

3.3.4 Impacts on atmosphere

The increased concentration of greenhouse gases in the atmosphere is the most important of the agricultural impacts that contribute to the process of climate change and global warming (IPCC, 2001; OECD, 2001). Agriculture contributes over 13.5% of the total greenhouse gas emissions worldwide (Herzog, 2006). In New Zealand, agriculture contributes close to 50% of the total greenhouse gas emissions (Ministry for the Environment, 2005).

The change in concentration of atmospheric CO_2 in recent times is a significant factor responsible for climate change (OECD, 1994). The other greenhouse gases associated with agriculture are methane emissions from livestock production and nitrous oxide from the soil. Greenhouse gases other than CO_2 are expressed in terms of their global warming potential (GWP) in relation to CO_2 (MAF, 2004; Mason, 2004; MED, 2007). The GWP of non-CO_2 gases is expressed relative to the effect of 1 kg of CO_2. For example, 1 kg N_2O has the same effect as about 310 kg of CO_2.

Agriculture is both a source and a sink for CO_2-equivalent emissions (Audsley, 1997; OECD, 1999). In agriculture, CO_2-equivalent emissions occur both directly and indirectly. The direct CO_2 emissions occur at the farm level, through fossil fuel use, microbial decomposition of organic matter, methane from livestock, nitrous oxide from the soil and oxidation of soil organic matter during biomass burning (OECD, 1994; Paustian et al., 2000). Indirectly, agricultural production is responsible for CO_2 emissions, due to indirect consumption of energy for the production of raw materials, such as fertilisers and machinery (Stolze et al., 2000; Dalgaard et al., 2001; Shepherd et al., 2003). Agriculture also acts as a sink of CO_2 in plant biomass and soil organic matter, through fixation of carbon in photosynthesis (OECD, 2001; Shepherd et al., 2003).

It is suggested that carbon acquisition and release from biomass should not be assumed in a steady-state[8] because not all the biomass is mineralised into CO_2 in the same year: a part of biomass is mineralised much more slowly over a period of years (Audsley, 1997; Rabl *et al.*, 2007). This means that carbon acquisition and release should be accounted at each stage of the life cycle (Rabl et al., 2007). Monitoring the role of agriculture as a source, as well as a sink for CO_2, is of considerable relevance for calculating the net burden of agriculture on the environment under the United Nations' Framework Convention on Climate Change (UNFCC) (OECD, 1999). Therefore, the net balance of the release and accumulation of CO_2-equivalent emissions has been suggested as an indicator of the contribution of agriculture to greenhouse gas emissions (OECD, 1999). This net balance approach provides a good reflection of agriculture's net contribution to climate change.

3.3.5 Impacts on biodiversity

Biodiversity is crucial to ecosystem services, that is, the services that nature supplies in terms of clean water and air, soil fertility, pollination, and the production of food, fuel, fibre and medicines (Costanza & Arge, 1997; EEA, 2007). The Millennium Ecosystem Assessment report, released in 2005, concludes that human activity has caused a substantial and largely irreversible loss of the Earth's biological resources (Millennium Ecosystem Assessment, 2005).

Land use for agriculture has had a direct impact on biodiversity, because production of crops and livestock products requires land largely cleared of native vegetation. The effects of energy and material flows on biodiversity and ecosystem services at the farm level takes place from the use of chemicals, the leaching of pesticides and nutrients to water and contamination of soil (Stoneham et al., 2003; Svensson et al., 2006). For example, fertiliser application may cause nutrient losses from agricultural soils that can encourage the growth of fertility-loving weeds and the dominance of a few species, due to eutrophication (Rennings & Wiggering, 1997).

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[8] Steady-state assumes that acquisition of CO_2 by plant biomass balances the release of CO_2 to the atmosphere.

The importance of biodiversity loss has been recognised with the signatures of representatives from over 150 countries in the Convention on Biodiversity, which arose out of the Rio Earth Summit in 1992. The proposed indicators of biodiversity are (OECD, 2001):

- Diversity within species (genetic level).
- Change in the number of species and their population size (species level).
- Changes in natural habitats providing the necessary conditions for populations of species (ecosystem level).

Although it is acknowledged that agriculture affects biodiversity, because of flows of energy and matter brought into the agricultural systems, it is not easy to demonstrate quantitative relationships between agricultural practices and biodiversity loss or degradation in ecosystem services. This limitation is due to methodological problems, the gaps in knowledge of the role of a particular species in the ecosystem and the uncertainty associated with the loss of a particular species (Hole et al., 2005). It has been acknowledged that it is difficult to recognise threshold factors for biodiversity loss that may cause irreversible damage to the ecosystems (Becker, 1997).

3.4 Organic orchard production systems and environmental impacts

As the focus of this research is the development of a practical approach to sustainability assessment at the organic orchard systems level, it is important to more specifically relate organic orchard systems to environmental impacts. Organic fruit production systems interact with, and impact on the environment in various ways. They use non-renewable resources; they affect soil, atmosphere and water quality; and they have an impact on biodiversity. While orcharding has negative (harmful) environmental impacts on the one hand, it also has positive environmental impacts[9] on the other. The negative environmental impacts include the emissions associated with the use of non-renewable energy and the use of copper containing fungicides, which have adverse effects on soil biodiversity (MAF, 1992; Edwards-Jones & Howells, 2001; Wood et al., 2006). The positive environmental impacts include the addition of organic matter to the soil as leaf litter and prunings, the growth of cover crops which reduce soil erosion, improvement in soil quality through recycled nutrients and sequestration of CO_2 in the plant biomass and the soil (OECD, 2004; OANZ, 2008).

Many countries, including New Zealand, recognise organic farming as one of the options that can reduce agriculture's negative impact on the environment and therefore improve sustainability (MAF, 1992; Stolze et al., 2000). Organic farming world-wide is defined by standards set for the achievement of environmental benefits. The implementation and control of these standards is the most important aspect differentiating organic farming from conventional farming (Stolze et al., 2000; Mouron et al., 2006).

The organic agriculture movement in New Zealand was initiated as a coalition of various interest groups and then formalised in 1983, with the establishment of the New Zealand Biological Producers Council (NZBPC). The NZBPC, later to be known as BioGro, set about formalising the standards by which production could be considered legitimately organic. The aims of the organic standards include reducing the risk of environmental contamination caused by runoff of nutrients, in addition to decreasing the levels of erosion by adopting appropriate land-use practices.

Kiwifruit and apples are the two most important export-oriented horticultural products in New Zealand. Organic growing is an important export-oriented activity in both sectors, contributing over 5% of the total kiwifruit area and 10% of the total apple area (MAF, 2004; Mason, 2004). Kiwifruit was originally commercialised in

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[9] Positive environmental impacts are the beneficial effects of orcharding on the environment. There is a general recognition of the need to improve environmental performance in agriculture, through enhancing the beneficial, and reducing the harmful environmental effects to ensure sustainability of resource use (OECD, 2004).

New Zealand when the first plantations were grown around the 1930s and in recent times New Zealand has emerged to be one of the leading kiwifruit growers of the world. New Zealand, together with Italy, accounts for about 70% of the world production of kiwifruit (FAS, 2007). In New Zealand, kiwifruit (26%) contributes the largest share of the total horticultural export earnings (MAF, 2007a). The apple industry is the second largest horticultural enterprise in New Zealand following kiwifruit and it contributes 18% of total horticultural export earnings (MAF, 2007a).

The key environmental issues associated with organic kiwifruit and organic apple production systems in New Zealand are examined below. These include the use of fossil energy, impacts on soil quality, CO_2-equivalent emissions to the atmosphere and impacts on biodiversity. In some cases, where there is no, or limited, information on organic kiwifruit and apple productions systems in New Zealand, reference is made to similar organic or conventional systems from other countries.

3.4.1 Energy use

Energy analysis has been considered as a way to identify the highest energy-consuming operations in fruit production systems (Reganold et al., 2001; Canals, 2003; ARGOS, 2005). Energy analysis is also carried out with the aim of reducing CO_2-equivalent emissions and helping New Zealand to meet its Kyoto Protocol[10] obligation (Watson et al., 2002; ARGOS, 2005).

There is limited literature available on the energy requirement of kiwifruit orchards. The median energy use for the twelve organic kiwifruit orchards studied in New Zealand was 35 GJ/ha/yr, and energy in fuels (direct energy) contributed to about 14 GJ/ha/yr (ARGOS, 2005).

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[10] The Kyoto Protocol is an international treaty on climate change, assigning mandatory emission limitations for the reduction of greenhouse gas emissions to the signatory nations. New Zealand ratified the Kyoto Protocol in December 2002. This international agreement commits New Zealand to reducing its net emissions of greenhouse gases over 2008-2012 (the first commitment period of the Kyoto Protocol or CP1) to 1990 levels.

The energy required to produce one tonne of organic apples in the Hawke's Bay district of New Zealand was estimated to be 1250 MJ (Canals, 2003). This includes the energy consumption in field operations, such as harvesting, managing pest and diseases, fertilising, pruning, thinning, protecting frosts, irrigating, and managing the understorey. Direct energy consumption in field operations is the major contributor of energy use in organically grown apples (Canals, 2003). According to a horticultural consultant in the Nelson district of New Zealand, the energy use and CO_2 emissions for the production of one tonne of conventional apples were reported to be 950 MJ and 60.1 kg respectively (Saunders et al., 2006).

The energy ratio (energy output divided by energy input) for organic apple systems in the USA was 1.18 over a six-year period. The average energy input per ha was 74.22 GJ/ha/yr, whilst the output energy in the fruit was 87.75 MJ/ha/yr. In another study of organic apple production in the USA, the energy output/input ratio for one year was only 0.06 because of the poor yield of 2.07 t/ha/yr and a high energy input of 20 GJ/ha/yr (Pimentel et al., 1983). This suggests that energy analyses of the orchard systems have shown mixed results. Pest control was the most energy-intensive input in an extensively managed apple orchard in Greece, contributing 40% of the total energy use, whilst energy in human labour was the smallest energy input contributing only 5% to the total energy used (Strapatsa et al., 2006).

3.4.2 Impacts on soil

Orcharding has both positive and negative impacts on the soil. It is predicted that Californian orchards sequester from 170 to 200 kg C/ha/yr in the soil (Kroodsma & Field, 2006; Kerckhoffs & Reid, 2007). Measures that could potentially increase soil organic matter content (compost applications, cover crops, etc.) are desirable for carbon sequestration in orchards (Schlesinger, 1999; Kroodsma & Field, 2006). Soil organic matter, such as compost also sequesters carbon (Shepherd et al., 2003). Application of compost and maintenance of orchard understorey (which is usually followed in organic orchards) is thought to increase levels of soil organic matter in the organic kiwifruit and organic apple orchards (MAF, 2004; Marsh et al., 2007).

Orcharding may also lead to negative impacts on soil, for example, nutrient mining from orchard soil. Kiwifruit and apples both have high requirements for potassium. However, most of the organic growers find it difficult to apply enough potassium to replace the amount lost due to crop removal (Haynes, 1998; Stowell, 2000). Many organic apple orchards studied in Ontario, Canada had phosphorus and potassium deficiencies in the orchard soil, suggesting the need for annual applications of these nutrients (Kessel et al., 2007). This is also true in New Zealand soils, where the soil potassium levels have slowly declined over a six-year study period in the organic kiwifruit system in the Te Puke region (Stowell & Barnett, 1996). The challenge in organic growing is to supply adequate quantities of nutrients from organic materials and other permitted fertilisers, so that the nutrients are not mined from the soil and the crop requirements are met without losses to the environment (Canals et al., 2006).

Soil compaction under wheel-tracks is another impact that may occur in orchard systems, due to the frequent passage of farm machinery in between the tree rows. Compaction is particularly an issue where heavy equipment (e.g. sprayers) is driven over the orchard surface, when the soil is wet. The extent of wheel-track compaction and whether it is a problem will depend on soil conditions, the frequency and weight of traffic and the type of fruit crop grown. In general, soil compaction issues are thought to be relatively higher in orchard crops which have extensive shallow lateral root networks that remain close to soil surface, than under deep rooted crops, which have roots that remain closer to the trunks (MAF, 2006b).

It is common to maintain a grass-legume understorey in organic orchard systems in New Zealand (Tutua et al., 2002). The maintenance of a grass-legume understorey minimises the effect of soil erosion and soil compaction, in addition to having the advantage of fixing nitrogen in the soil through legumes (Granatstein, 2000; Tutua et al., 2002).

3.4.3 Impacts on water

Leaching of nitrate nitrogen is one of the important impacts of orchard production practices on water resources. In organic systems, compost and other products (foliar fish fertiliser, blood and bone, stick water – a by-product of fish industry) and the nitrogen accumulated by legumes are potential threats of nitrate leaching (Stopes et al., 2002). A study in the USA recorded nitrate N concentrations of 20-26 mg N/L in the leachate from a conventional apple orchard, whilst N-leaching losses of 50 kg/ha/yr were predicted from a conventional kiwifruit orchard in New Zealand (Ledgard et al., 1992; Merwin et al., 1996).

To protect human health, the World Health Organisation (WHO) has established 11.3 mg of nitrate N/L of water as a maximum allowed level of nitrogen in water (Di & Cameron, 2002; Ju et al., 2006). The level proposed by the WHO is the most commonly used threshold level for nitrogen in New Zealand. However, levels as low as 0.5 mg of N/L of water have been considered as a potential threat to ecosystem health through ensuing eutrophication (Pierzynski et al., 2005).

3.4.4 Impacts on atmosphere

Orchard production emits as well as sequesters CO_2. Orchard crops play a positive role in the global carbon cycle through carbon sequestration in the woody plant biomass and the low-till nature of their soils (Kerckhoffs & Reid, 2007). The negative impacts of the orchard production practices occur through emissions of nitrous oxide in the process of denitrification (Di & Cameron, 2002), emissions from the use of fossil fuels (Mouron et al., 2006), and CO_2 emissions from soil organic matter oxidation (Grogan & Matthews, 2002). The net numerical difference between CO_2-equivalent sequestration and emissions has been viewed as a measure of the relative contribution of the orchard system to the carbon cycle (Kerckhoffs & Reid, 2007).

3.4.5 Impacts on biodiversity

Orcharding has positive as well as negative impacts on biodiversity. Orchard management practices, such as the use of machinery, might affect soil biodiversity adversely, due to soil compaction. On the other hand, preliminary results in kiwifruit orchards in New Zealand suggested that shelter-belts, which are the areas less visited by machinery, can harbour higher above-ground biodiversity (Moller et al., 2007). On-site composting has been also shown to increase the number of insects and spiders in kiwifruit orchards (ARGOS, 2005).

The use of copper-containing compounds as fungicides is an important practice in organic fruit production systems in New Zealand (Daly, 1994b). A substantial amount of copper sprayed annually reaches the soil, where it often remains fixed in the surface layers. Higher levels of copper that accumulate in the top-soil impact adversely on soil biodiversity (Merrington et al., 2002; Morgan & Taylor, 2003/2004; Saunders et al., 2006; Sonmez, 2007).

Copper is a restricted compound in organic growing and its application rate is limited to 3 kg Cu/ha/yr by the BioGro organic certification agency (BioGro, 2004; MAF, 2004). The maximum acceptable concentration of copper for environmental sustainability in orchard soil is 60 mg/kg (Van-Zwieten et al., 2004). Overall, soils from horticultural properties have been found to contain higher levels of copper than pastoral soils, which may be because of the widespread and prolonged use of copper-based fungicides on horticultural properties (Gaw et al., 2006).

3.5 Analytical approach for sustainability assessment at the orchard systems level

The concept of sustainability, the various interpretations of agricultural sustainability, various approaches to sustainability assessment and the important impacts of agriculture and organic orchard practices on the environment have been described so far. With that as a foundation, this section is focused on developing an analytical approach for sustainability assessment at the orchard system level. The criteria for sustainability are based on the laws of thermodynamics, as explained in Chapter 2. In this section, appropriate indicators which are consistent with the criteria for sustainability are identified, in order to apply them at the orchard systems level. Definitions of the orchard systems and orchard systems boundaries are also presented.

3.5.1 Criteria and indicators for sustainability assessment at the orchard systems level

The orchard system interacts with the natural environment in which it is embedded, through energy and material flows (Figure 3.1). The energy and material flows are constrained by the laws of thermodynamics and they have impacts on the natural environment (Ruth, 1993).

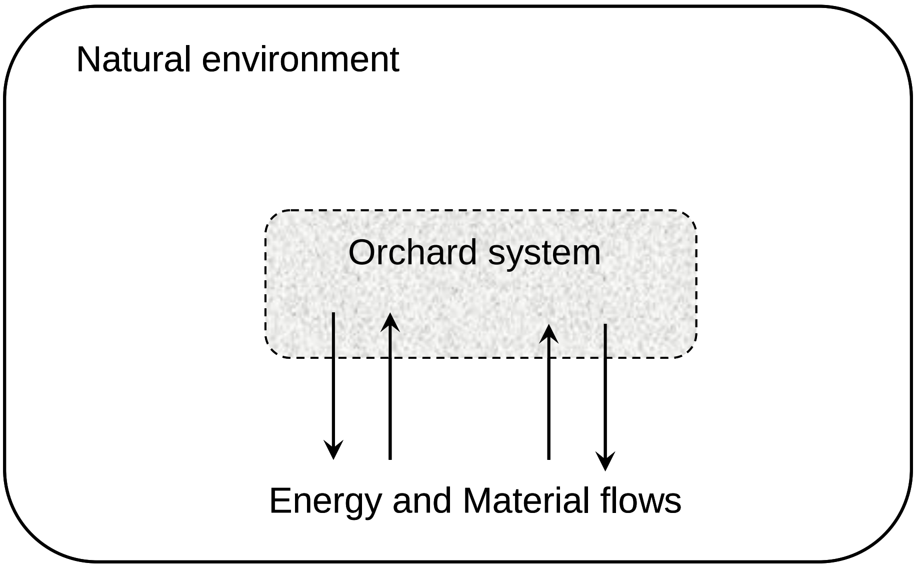

Figure 3.1 Orchard system and the environment (Adapted from Ruth, 1993)

Energy flows, especially those derived from non-renewable resources, have links with material flows and they are associated with negative environmental impacts, such as the release of CO_2 and other greenhouse gases (Svensson et al., 2006). Material use also affects the energy use, since the use of inputs such as fertilisers or machinery or any other production input has energy embodied in them (since matter contains energy). Thus, the energy use of the system changes as new matter is brought into the system (Ruth, 1993). Also, the use of material inputs, such as fertilisers or machinery, may have environmental impacts affecting soil, air, water and biodiversity. Management decisions are important in deciding the magnitude and type of energy and material use on the orchard, which may have varying degrees of impacts on the environment (Ruth, 1993).

As derived in Chapter two, sustainability at the farming systems level can be reduced to two high level criteria: energy criterion and impact criterion. Energy criterion implies that energy use of the orchard systems should be efficient and the impacts criterion implies the non-degradation of the environment from energy and material use (Daly, 1990; Ruth, 1993; Scheraga, 1994). These high level criteria need to be more specifically defined for application at the orchard systems level. This entails identifying appropriate indicators that are consistent with energy efficiency and non degradation of the environment from energy and material use. In this research, five indicators for assessing sustainability at the orchard systems level are suggested. The indicators are presented in Table 3.1. Each indicator and its threshold value for sustainability is described in detail below.

Table 3.1 Indicators of sustainability at the orchard systems level

Criteria	Positive impacts	Negative impacts	Indicators of sustainability
Energy efficiency (energy criterion)	Food energy output	Direct and embodied energy use	Energy ratio
Non-degradation of the environment due to energy and material use (impact criterion)	CO_2 sequestered by the fruit trees (photosynthesis)	CO_2 emitted from direct and embodied energy use and the soil	CO_2 ratio
	Soil carbon sequestration	Soil carbon loss	Changes in soil carbon level
	Building of soil fertility/structure	Mining of soil nutrients	Nutrient balances
	–	Higher concentration of N in water	N-leaching

3.5.1.1 Energy ratio

The energy ratio is the efficiency of conversion of energy input to fruit energy output. Energy output is the energy in fruit that is physiologically available[11] for humans and energy input is the direct and embodied energy, both expressed in thermal equivalents. The direct energy and the embodied energy take into consideration the following:

- Direct energy – energy used in fuels, lubricants and human labour for carrying out various operations.
- Embodied energy – energy used in manufacture, packaging and delivery of all inputs such as agrichemicals, machinery and fertilisers to and within New Zealand.

The energy output/input ratio should be one or more, in order for the orchard production system to be energy efficient (Reganold et al., 2001; Fakhrul Islam et al., 2003; Schlosser et al., 2003).

3.5.1.2 CO_2 ratio

The CO_2 ratio considers the impacts on the atmosphere in terms of greenhouse gas emissions. It is the ratio of carbon sequestered to carbon emitted, expressed in CO_2-equivalent units. Carbon is sequestered in vines/trees in the process of photosynthesis and temporarily in compost (Shepherd et al., 2003; Kroodsma & Field, 2006). Carbon equivalent emissions occur from the carbon emissions from direct and embodied energy use, from decomposition of mulched prunings, leaves, fine roots and compost and as nitrous oxide emissions from the orchard soil (Di & Cameron, 2002; Grogan & Matthews, 2002; Mouron et al., 2006). The CO_2 ratio has to be one (the system is carbon neutral) or higher than one (the system is net carbon sink), so that the greenhouse gas emissions do not accumulate in the atmosphere and the system is sustainable (Robert, 1997).

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[11] Physiologically available energy is the energy obtained by subtracting energy lost in the excreta from the total energy value of the food.

3.5.1.3 Changes in the soil carbon level

Soil carbon level is an important indicator of soil organic matter, which in turn is an indicator of soil quality. Changes in the soil carbon level are estimated as a balance between carbon input and carbon loss. Sequestration of carbon in the soil enhances soil quality and occurs when the carbon input exceeds carbon loss (Johnston, 1986; Audsley, 1997). Carbon input is through the addition of organic matter (prunings which includes leaves and stems, compost and root decomposition). However, not all the carbon that enters the orchard soil through organic matter stays in the soil. Carbon loss occurs as microbial decomposition of organic matter (Paustian et al., 2000). Hence, in order for an orchard system to be sustainable, the orchard soil should sequester carbon, which means that the carbon input should be higher than the carbon loss.

3.5.1.4 Nutrient balances

Nutrient balances are an important indicator of soil quality. It is estimated as a balance between the input of nutrients from fertilisers, soil mineralisation, rainfall, and cover crops, and the output or withdrawal of nutrients from the soil in fruit, plant, leaching and gaseous losses (Di & Cameron, 2002). When nutrient inputs are in balance with nutrient outputs, then the crop requirements are met and there is no surplus of nutrients that may be lost to the environment. A negative nutrient balance (nutrient deficit) indicates that the system relies on mining soil nutrient reserves and it is not sustainable. A positive nutrient balance (nutrient surplus) is generally considered sustainable, especially because poor soil fertility is a constraint to future crop production (Harris, 1998). However, a large surplus of nutrients increases the chances of nutrients being lost to the environment, possibly with negative consequences.

3.5.1.5 Leaching of N

Leaching of N from the organic orchard systems is an important indicator of the potential threat of eutrophication (Di & Cameron, 2002). It is thought that the level of N-leaching, which can indicate a potential threat of eutrophication, is much lower than the one proposed by the WHO. The exact level of N-leaching, that is a potential threat of eutrophication, depends on the particular ecosystem However, a system is potentially considered as eutrophic, even when the concentration of N in water is as low as 0.5 mg N/L (Pierzynski et al., 2005). Following Pierzynski et al (2005), an orchard system is considered to pose a potential threat of eutrophication, if the leaching level of N is higher than 0.5 mg N/L.

In order to carry through the sustainability assessment in this research, the above five indicators along with their threshold levels are considered. The five sustainability indicators are based on the major impacts associated with organic orchard systems in New Zealand. The indicators cover impacts of orchard production practices occurring on the soil, water and the atmosphere. These indicators have analytical soundness and have been acknowledged to be relevant in policy and research, as identified from the literature. Also, they track the long term trend for sustainability in a retrospective perspective and therefore they help to make informed decisions as to how management practices can be more sustainable.

There are potentially other environmental impacts associated with organic orchard production systems that are not considered in sustainability assessment in this research. These are soil erosion and soil compaction. The growers of the organic orchard systems usually maintain permanent grass-legume understorey vegetation between the rows, which minimises soil erosion and soil compaction. Soil erosion and soil compaction have not been reported as major issues of environmental relevance for organic kiwifruit and organic orchard systems in New Zealand. Hence, they are not considered in this research. Also pesticides, which are usually prepared using artificial chemicals are generally prohibited under official organic certification standards (BioGro, 2004). Therefore, contamination of water by pesticides is not considered as an environmental impact from the organic orchard systems.

It is acknowledged that sustainability assessment, based on energy and material use, can be related to some environmental impacts more strongly than others. For example, the loss of biodiversity and degradation in ecosystem services are not directly represented through energy and material flows at the orchard systems level (Gudmundsson & Hojer, 1996; Svensson et al., 2006). However, in practical terms, the criteria for non-degradation of the environment also mean that biodiversity and ecosystems services should not be irreversibly impacted in the long term, due to orchard production practices. It is acknowledged that orchard production affects biodiversity and ecosystem services adversely, through the destruction of existing natural ecosystems that are cleared for orchard establishment. However, as already described, identifying the threshold level for the degradation of these services remains a challenge and it might not even be feasible (Becker, 1997). Therefore, there is no attempt to quantify biodiversity loss and degradation in ecosystem services, due to energy and material use in this research. However, impacts on biodiversity are indirectly considered in this research, through the level of potential N-leaching that may be a threat of eutrophication.

3.5.2 Defining the organic orchard system

Systems' thinking is an appropriate approach to sustainability assessment (MacRae et al., 1989). Systems' thinking is based on the belief that the component parts of the system can best be understood in the context of relationships with each other and with the environment, rather than in isolation. A system can be defined as:

> "a group of interacting components, operating together for a common purpose, capable of reacting as a whole to external stimuli; it is unaffected directly by its own outputs and has a specified boundary based on the inclusion of all significant feedbacks" (sic) (Spedding, 1988 p. 18).

The first task in sustainability assessment is to define the orchard system and identify the system boundary. The orchard system consists of the fruit trees, soil system and the atmosphere. At a higher hierarchical level, the orchard system is connected to the natural environment in which it is embedded. There are continuous energy and material flows within and between the orchard system and the natural environment. Given that the different levels are linked and affect each other, sustainability analysis of orchard systems should consider all of these levels.

The purpose in this research is to assess orchard system sustainability, with sustainability defined according to the laws of thermodynamics. Orchard production systems are thermodynamically open, which receive inputs from, and release outputs to, the natural environment (Figure 3.2). However, as orchard systems are embedded within the closed system of the Earth, they cannot exist independently of the natural environment (Svirezhev, 2000). Thus, for sustainability assessment, orchard systems are considered together with the natural environment with which they interact.

Energy and material flows within the orchard and between the orchard systems and the environment are identified, based on life cycle thinking. Life cycle thinking helps to keep in mind that the entire system needs to be studied for sustainability assessment, to account for the system-wide environmental impacts. The management decisions on the orchard dictate the magnitude of energy and matter inputs to the orchard system (Figure 3.2). The fruit trees transform these inputs into fruit energy output. Simultaneous material flows of CO_2-equivalent emissions occur to the atmosphere, when energy inputs are used. Inputs such as fertilisers, affect soil quality and water quality. A part of the CO_2-equivalent emissions are recycled in plant biomass through photosynthesis. A portion of organic matter that enters the orchard soil stays there, whilst the rest is emitted to the atmosphere as CO_2-equivalent emissions. All these interactions need to be considered in sustainability assessment.

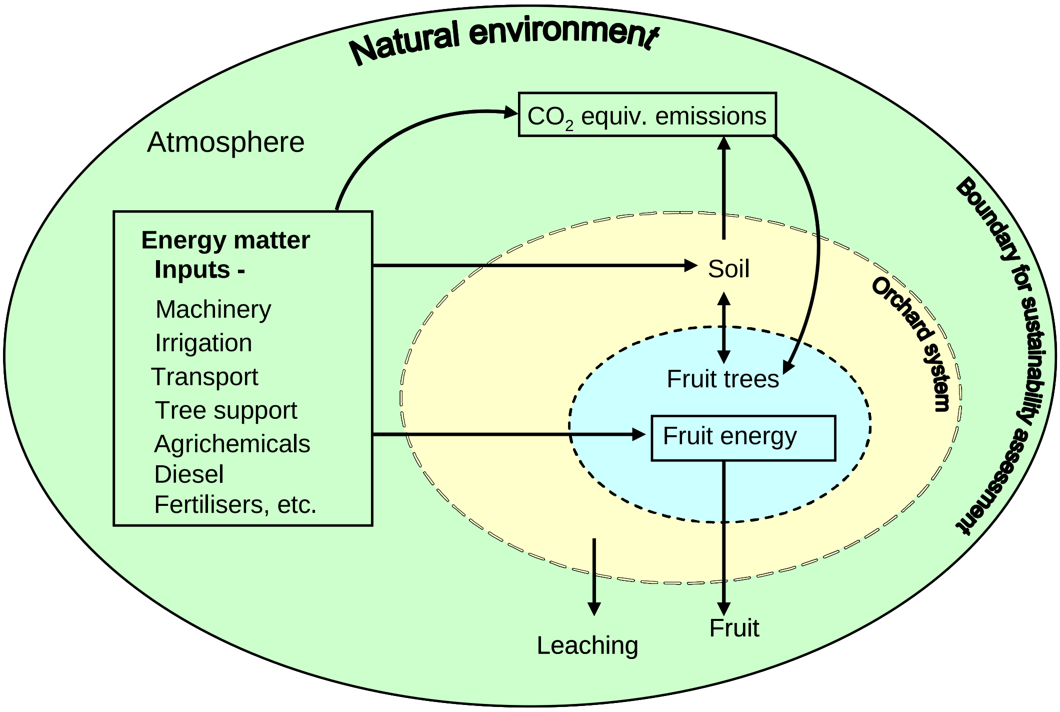

Figure 3.2 Schematic diagram of an orchard system for sustainability assessment
The arrows represent energy and material flows. The orchard system is embedded in the natural environment. For sustainability assessment, the orchard system is considered together with the natural environment with which it interacts.

3.6 Summary

From the review, it is clear that there is no sustainability assessment approach which integrates energy and material flows and their impacts on the environment that is practically applicable at the farming systems level. To fulfil this gap, an analytical approach to sustainability assessment at the orchard systems level is proposed with appropriate indicators and threshold levels. To undertake sustainability assessment, the orchard system boundary is defined to include the major energy and material flows between the orchard and the natural environment.

The methodology, with which to apply the analytical approach to the organic orchard production systems, is explained in the next chapter.

Chapter 4

METHODOLOGY

4.1 Introduction

In the previous two chapters, the theoretical foundation for sustainability and the analytical approach to sustainability assessment, at the orchard systems level, were elaborated upon. The aim in this chapter is to describe the methodology, in order to apply the proposed analytical approach to assess sustainability of the organic kiwifruit and organic apple systems in New Zealand. The organic orchard system boundary for sustainability assessment is considered together with the energy use and environmental impacts arising from orchard production practices, until the fruits reach the pack-house. The organic orchard system is described, based on the primary data gathered directly from the growers. The primary data includes information relating to the orchard production practices and other miscellaneous information. Parameters, which are essential to convert primary data into appropriate energy or material values, in order to estimate sustainability indicators, are gathered from the secondary data (published literature). Appropriate computer modelling tools, that enable the estimation of sustainability indicators using the primary and secondary data, are identified.

4.2 Primary data collection

The first task, in sustainability assessment of the organic kiwifruit and organic apple production systems in New Zealand, was to develop a model of these systems, based on the real orchards. A model of an organic orchard production system, for sustainability analysis, was the conceptualisation of the key interactions between the orchard production practices and the natural environment, as they occur in the real orchards. The orchard systems interact with the natural environment, through management decisions. Management decisions influence the energy and material flows between and across the orchard and the environment. In order to model each organic orchard system, complete information was therefore required on how these systems were managed: this includes the energy and matter inputs that were brought in by the orchard manager, in order to carry out various production practices. Primary data on orchard production practices within organic orchards were gathered through semi-structured interviews with either the growers or the orchard managers. These included the calendar of key operations and the various inputs used in carrying out those operations, during a typical production year. For each orchard, information was collected on orchard establishment, such as the rootstock, the plant spacing, the training system and the type of irrigation and frost protections system (when used). Information on site-specific characteristics included the topography and soil type and whether the site was prone to frosts or required irrigation. Information was also collected on the orchard's gross yield per ha (the fruit picked) and other miscellaneous factors, such as the distance to the pack-house, the method of pruning disposal, management of the understorey, the frequency and rate of compost application and the electricity usage for irrigation.

The information requested from the growers or orchard managers was guided by a set of questions (see Appendix I). The questions were the same for both kiwifruit and apple growers, except for the first page. The questions served as a guide only and the interviewees were given the opportunity to expand on any points that they thought were important.

Primary data were collected in the North Island of New Zealand (Figure 4.1). The Bay of Plenty and the Hawke's Bay, respectively are the largest kiwifruit and apple producing and exporting districts of New Zealand (Statistics New Zealand, 2006). In 2005, the total area under kiwifruit in the Bay of Plenty was 9,100 ha out of a total of 12,030 ha under kiwifruit in New Zealand. Hawke's Bay, in 2005, had an area of 6,070 ha under apples, out of a total 10,980 ha under apples in New Zealand. These regions also had the largest areas under certified organic kiwifruit and apple production, respectively.

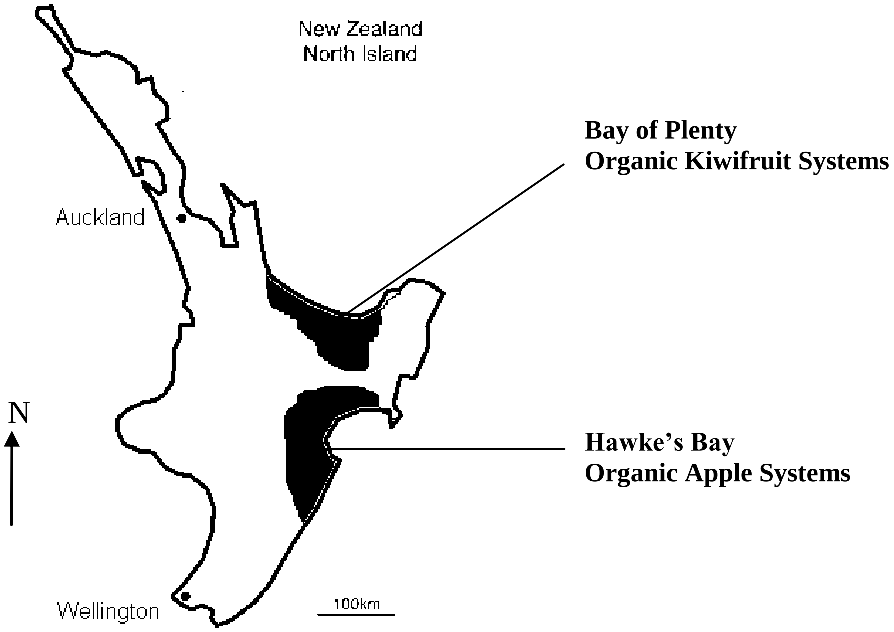

Figure 4.1 Study area

In organic growing, there is substantial freedom for orchard management practices, within the guidelines of the official organic production standards (Mouron et al., 2006). In order to cover a range of production-specific data on orchard production practices, primary data were gathered from a number of organic kiwifruit and organic apple orchardists. The orchards that were selected ranged from relatively small to relatively large operations. After interviewing five organic kiwifruit and five organic apple growers, it was concluded that the key annual production practices and the range of inputs used on a per hectare basis across the orchards were more or less similar, so therefore no further orchardists were interviewed. A model organic kiwifruit system and a model organic apple system, typical of the orchards studied, were then derived and a sustainability assessment was undertaken for these model systems. It must be noted that it was not the purpose of this research to generalise beyond the studied orchards, in order to answer the question of whether the organic kiwifruit and organic apple systems in New Zealand are sustainable. The purpose, instead, was to apply the proposed assessment to the model systems, in order to identify key factors that influence the sustainability of these systems. Application of the proposed sustainability assessment approach, to the organic orchard systems, also helps to determine whether this approach is appropriate and it is useful for assessing sustainability in more general terms.

4.3 Data from published literature

A number of coefficients were gathered from the published literature to convert primary data into appropriate energy and material values, in order to estimate sustainability indicators. The two high level criteria for orchard system sustainability are energy efficiency and non-degradation of the environment from energy and material use (see Chapter 2 for the theoretical argument). The five sustainability indicators, consistent with these criteria, are energy ratio, CO_2 ratio, a change in soil carbon level, nutrient balances and leaching of N (Table 3.1). The coefficients that correspond to the estimation of these sustainability indicators are described below.

4.3.1 Energy ratio

The energy ratio indicates the efficiency of conversion of energy in input to fruit energy output. It is expressed as follows:

$$Energy\ ratio = \frac{Energy\ output\,(MJ/ha/yr)}{Energy\ input\,(MJ/ha/yr)} \qquad 4.1$$

4.3.1.1 Energy output

Energy output is the MJ of energy in the fruits produced. Data on the edible energy content of kiwifruit and apples were obtained from the Food Nutrient Database (USDA, 2007). The energy content in fruit represents the physiologically available energy (energy available to do work) for humans. The physiologically available energy content for kiwifruit is 2.5 MJ/kg and for fresh apples it is 2.18 MJ/kg (USDA, 2007). In a study carried out by Strapatsa et al (2006), the energy content in apples was reported to be 2.4 MJ/kg, whilst Reganold et al. (2001) reported an energy content of 2.34 MJ/kg. However, these authors did not specify whether the reported energy content of fruit was the physiologically available energy or the gross energy (heat of combustion). Hence, in this study, an energy content of 2.18 MJ/kg of fresh apple fruit is used, following USDA (2007). Output energy (MJ/ha/yr) is calculated as:

$$Energy\ output\ (MJ/ha/yr) = Fresh\ fruit\ (kg/ha/yr) * fruit\ energy\ content\ (MJ/kg) \qquad 4.2$$

4.3.1.2 Energy input

Energy input (MJ/ha/yr) is the sum of direct and embodied energy used for carrying out all of the operations in the orchard production systems, including spraying, fertilising, harvesting, transporting, irrigating, mowing, mulching, frost fighting and shelter-trimming. Energy input is estimated as:

$$Energy\,input = \sum(E_{\mathrm{direct}} + E_{embodied}) \qquad 4.3$$

An issue with the estimation of embodied energy is the decision as to where the energy accounting process should be truncated. For example, the energy embodied in a tractor includes the energy expended in the manufacture of the tractor and the energy in the manufacture of the machines that produced the tractor and so on. It was assumed that the energy costs, beyond those of fuels, materials and labour, used to produce the machines and materials which are used on the farm, make an insignificant contribution to the total energy cost and they were therefore disregarded (Foster & Matthews, 1995). The direct and the embodied energy are described below.

Direct energy

Direct energy is the summation of energy in fuel and energy in human labour hours used and it is expressed in MJ/ha/yr as follows:

Direct energy (MJ/ha/yr) = fuel energy (MJ/ha/yr) + human labour energy (MJ/ha/yr)

4.4

Fuel energy

The gross energy contents of diesel, petrol and lubricants are estimated to be 38.0 MJ/L, 34.5 MJ/L and 40 MJ/L, respectively (Wells, 2001). An extra 23% is added to these values, to account for the energy used in extraction, processing, refining and transporting to and within New Zealand (Wells, 2001). This gives the total energy content for diesel, petrol and lubricant as 46.7, 42.3 and 49.2 MJ/L, respectively (Wells, 2001). Fuel energy is the sum of *n* types of fuel (petrol, diesel, lubricants) and it is expressed as:

$$Fuel\ energy = \sum_{n} energy\ content\ of\ \ fuel * \ fuel\ used \qquad 4.5$$

Fuel consumption, per operation per pass, is derived from the grower’s estimation of the average time required to carry out that operation on a per ha basis and the type of machinery used. It is assumed that fuel consumption does not vary significantly between different makes and models of diesel engines, or different sizes of engine, when compared to the basis of power take off (PTO[12]) (Martin, 2003). PTO allows for transmission and hydraulic system losses and therefore it represents the actual power the machine can develop, in order to do work. Fuel consumption for diesel engines is approximately 0.35 L/hr for every kW of PTO (Martin, 2003). To convert horsepower (hp) rating to PTO (kW), hp is multiplied by 0.7457 (Martin, 2003).

Diesel engines are not designed for operating at maximum horsepower for prolonged periods of time (Martin et al., 1986). For example, tractors use on average only 55 to 60% of their maximum horsepower on a year-round basis (Downs & Hansen, 1998). In this study, the tractor is assumed to use an average of 60% of maximum horsepower, for carrying out various operations on an annual basis.

A 50 kW tractor, working at 60% of maximum power, will consume 10.5 L of diesel per hr (50 kW x 0.60 x 0.35 L/hr). Accordingly, the fuel consumption can be calculated on the basis of time per ha required for each operation. Although fuel consumption depends on the shape, size and topography of the orchard and the driver’s personal skill in using the machine efficiently, these factors were assumed to not affect fuel consumption significantly enough for this research. Thus, the diesel consumed by a tractor working with 60% efficiency is estimated as:

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[12] PTO, a device that transmits the power of the tractor’s engine to the machines attached to the tractor.

$$Diesel(L/hr) = kW*0.35\ (L/hr)*\ 0.60 \qquad 4.6$$

Not all the operations within an orchard are undertaken by the grower/manager. Some operations, such as the application of fertilisers, harvesting and transporting the fruit to the pack-house and shelter-trimming are sub-contracted. Fuel consumption in these operations is calculated from estimates of the machinery used and the time required for carrying out the work in the orchards. Transport of fruit to the pack-house and the delivery of the compost from the supplier to the orchard are considered to require 3 MJ per tonne*km of fruit, assuming diesel as the fuel (Bone et al., 1996).

Human energy

Human labour forms an important input into the farming system and needs to be accounted for. Human labour represents a renewable energy resource and it is estimated as the sum of human labour use for all the operations as person-days/ha/yr. Operations, such as pruning, thinning and harvesting are usually done manually. Human labour is also required to: prepare sprays; undertake the paperwork for obtaining organic certification; carry out pest monitoring, repairs and maintenance; and other miscellaneous activities in the orchard.

Direct energy, expended through human labour, is essentially the food energy utilised by the body, whilst the work is being performed. The human body converts chemical energy from food to the mechanical energy of work. It is estimated that a farm labourer consumes 21,770 kcal of food energy per week and works 40 hours per week (Pimentel et al., 1973). For eight hours, which is considered to be a one person-day, the direct energy requirement comes to 4354 kcal or 18,287 kJ (1 kcal = 4.2 kJ). This figure (18.3 MJ) is used in this study for a one person-day of human labour. Hence, the total MJ energy expended in human labour is calculated as:

$$Human\ energy\ (MJ/ha/yr) = no\ of\ person\text{-}days/ha/yr*18.3\ MJ/day \qquad 4.7$$

Embodied energy in human labour is the energy that is expended in growing, processing and distributing the food needed to support a labourer, through the period of work. However, embodied energy in human labour is not considered in this study, for the reason that people exist (and must eat) irrespective of their occupation (Audsley, 1997). Hence, only the direct energy in human labour is considered.

Embodied energy

Embodied energy is the sum of embodied energy in *n* production inputs, which may include embodied energy in materials, such as fertilisers and agrichemicals, compost, tree support, machinery or implements, electricity usage and irrigation system. Embodied energy is represented as:

$$\text{Embodied energy (MJ/ha/yr)} = \sum_{n} (E\ embodied) \qquad 4.8$$

The embodied energy in individual inputs is described below.

Embodied energy in fertilisers and agrichemicals

Growers in organic orchards in New Zealand use different materials, such as fertilisers, fungicides, insecticides or biostimulants. The fertilisers include natural forms of potassium sulphate, gypsum, dolomite, natural rock phosphate, biomineral calcium, magnesium sulphate, fish meal (product of fish processing industry), blood and bone (product of meat processing industry) or other organic fertilisers from microbiological technology. Insecticides in organic orchards usually include biocontrol agents (*Bacillus thuringiensis*, macrocyclic spinosad), elemental sulphur, copper and mineral oil. There are other organic materials called biostimulants, which are used for spraying organic fruit crops. These include seaweed, fish oil, molasses, bud-enhancers and compost tea (a liquid solution or suspension made by steeping compost in water). These materials are derived from natural sources or they are products of industrial waste. The embodied energy content of the various material used in the organic orchards are presented in Table 4.1. In order to estimate the embodied energy for the amount of inputs used, the respective embodied energy coefficient from Table 4.1 is multiplied by the amount of input used in kg or L (also includes embodied energy in non-active ingredients).

Table 4.1 Embodied energy coefficients in inputs

Input	Embodied energy coefficient	Source
Rock phosphate	15 MJ/kg P	(Wells, 2001)
Agricultural Lime	0.6 MJ/kg	(Wells, 2001)
K in fertilisers	10 MJ/kg K	(Wells, 2001)
S in fertilisers	5 MJ/kg S	(Wells, 2001)
Mg in fertilisers	5 MJ/kg Mg	(Wells, 2001)
Sulphur as fungicide	111.47 MJ/kg S	(Pimentel, 1980)
Copper as fungicide	111.47 MJ/kg Cu	(Pimentel, 1980)
Mineral oil as insecticide	29 MJ/L	(A. Barber, 27 July, 2007, personal communication
Biostimulants	5 MJ/L	(Adapted from Helsel, 1993[13])
Bacillus thuringiensis	120 MJ/kg Bt	(Barber 2004, cited in Saunders et al., 2006)
Macrocyclic spinosad	120 MJ/ L spinosad	(Barber 2004, cited in Saunders et al., 2006)
Organic fertilisers	5 MJ/kg	(Adapted from Helsel, 1993)

The energy embodied in a fertiliser includes the energy content of raw materials and fossil fuels used in its manufacture, in addition to the energy associated with packaging, transport and distribution (Mudahar & Hignett, 1987; Wells, 2001). Organic fertilisers are less energy intensive, than inorganic fertilisers (Florida Energy Extension Service & Helikson, 1991). Inorganic fertilisers are mostly prohibited or restricted under the organic certification standards (BioGro, 2004).

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[13] Helsel (1993) has estimated the embodied energy content of organic materials (used as fertiliser or spray) to be 3.5 MJ/kg. A small amount of additional energy is assumed for the formulation. Helsel estimates energy for formulation of organic materials to be approximately 1 MJ/kg), plus a small amount of energy in the transport. In this study, the embodied energy content for organic fertilisers is considered to be 5 MJ/kg.

The embodied energy for compound fertiliser [14] is determined by multiplying the percentage of the individual nutrient in the final fertiliser with the appropriate energy coefficient, as described in Table 4.1, and then summing these figures. The nutrients presented in Table 4.1 are supplied from potassium sulphate, kieserite and/or magnesium sulphate (the nutrient contents of these mineral fertilisers are presented in Appendix II). The active ingredient in biostimulants is assumed to be 100%. The percentage of active ingredient in spray inputs is presented in Table 4.2.

Table 4.2 Active ingredients in spray inputs

Agrichemical	Active ingredient	Source
Bacillus thuringiensis	54% BT subsp. Kurstaki	(Valent, 2006)
Macrocyclid spinosad	80% spinosad	(Dow AgroSciences, 2007)
Lime sulphur	22% calcium polysulphide	(United Agri Products Canada Inc., 2008)
Sulphur fungicides	80% sulphur	(Kumulus DF, 2006)
Copper fungicides	54% copper	(Du Pont, 2008)

Thus, embodied energy in fertilisers or agrichemicals is estimated as:

*Embodied energy in fertilisers/agrichemicals (MJ/ha/yr) = amount of input used/ha/yr * appropriate energy coefficient from Table 4.1* *4.9*

Embodied energy in compost

It was estimated that 1.1 MJ of energy is required to prepare every kg of compost dry matter (Barber & Scarrow, 2001). The dry matter content of the BioGro certified compost ranged between 50-53% of the fresh weight. In this study, the dry

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[14] Compound-fertiliser contains two or more elements e.g. potassium sulphate (K and S), magnesium sulphate (Mg and S).

matter content of compost was assumed to be 50%. The embodied energy in compost is estimated as:

$$\text{Embodied energy in compost (MJ/ha/yr)} = \text{Amount of compost (kg/ha/yr)}*1.1(\text{MJ/kg})*0.5 \qquad 4.10$$

Embodied energy in machinery and equipment

The machinery and equipment used in carrying out various operations include a tractor, sprayer, mulcher, mower, utility vehicle (ute), forklift, shelter trimmer, truck, trailer and helicopter. The energy coefficient for each of these items of machinery/equipment and their working life is presented in Table 4.3. The embodied energy for an individual piece of machinery/equipment is expressed as**:**

Embodied energy (MJ/ha/yr) =

$$\frac{Embodied\ energy\ coeff.(MJ/kg)(Table\ 4.3)*weight(kg)}{working\ life\ (yrs)} \qquad 4.11$$

Table 4.3 Energy coefficients and working life of vehicles and implements

Machinery/equipment	**Embodied energy coefficient**	**Working life (yrs)**
Tractors	160 MJ/kg	15
Trucks	160 MJ/kg	15
Farm implements *	80 MJ/kg	20
Forklift	160 MJ/kg	15
Shelter trimmer	160 MJ/kg	15
Helicopter	160 MJ/kg	15

Source: Wells (2001)
**mower, sprayer and trailer.*

The embodied energy of the tractor is allocated in proportion to the number of hours the tractor is used in carrying out various operations, such as mowing, mulching, harvesting and spraying. The mass of a tractor, forklift and shelter-trimmer were estimated on the basis of the equation 4.12 following Wells (2001) as:

$$\text{Mass} = 40.8 * \text{power (hp)} + 190 \text{ (kg)} \qquad 4.12$$

Embodied energy in tree/vine support

The orchard crops usually require support for the growing plants, such as wooden posts and galvanised wires. The wooden post is considered to have an energy cost of 18 MJ/post, and galvanised 2.5 mm high tensile wire has an energy content of 1.3 MJ/m (Barber & Scarrow, 2001). The embodied energy per ha per yr, in a training system, is estimated as per the following equation and it is allocated over 20 years:

$$\text{Embodied energy in tree/vine support (MJ/ha/yr)} = [\text{embodied energy in wooden posts (MJ/ha)} + \text{embodied energy in galvanised wires (MJ/ha)}]/20 \qquad 4.13$$

Embodied energy in electricity

Electricity in orchard production is mainly used for irrigation. The embodied energy content in electricity is 7.45 MJ/kWh (Barber & Lucock, 2006). This value accounts for the energy expended or lost during extraction, refining, generation, conversion, transportation and distribution in New Zealand, considering that 62% of electricity generation comes from renewable resources (wind and hydro).

$$\text{Energy in electricity (MJ/ha/yr)} = \text{electricity usage (kWh/ha/yr)} * 7.45 \text{ MJ/kWh} \qquad 4.14$$

Embodied energy in irrigation systems

The total energy associated with orchard irrigation is a combination of embodied energy in well drilling, pumping equipment and pipes and this is allocated over one year and one hectare, respectively (Barber & Scarrow, 2001; Wells, 2001; Saunders et al., 2006). Embodied energy in an irrigation system is:

Embodied energy in irrigation system (MJ/ha/yr) = embodied energy in well drilling (MJ/ha/yr) + embodied energy in pumps (MJ/ha/yr) + embodied energy in pipes (MJ/ha/yr) *4.15*

Well drilling is estimated to have an energy cost of 400 MJ/m (Saunders et al., 2006). The life of a well is assumed to be 100 years.

Pumps have the same energy cost to manufacture as vehicles, at 160 MJ/kg (Saunders et al., 2006). The working life of a pump is assumed to be 15 years.

The energy in the pipes is a combination of energy in the mainline, energy in the sub-main and energy in the laterals (Saunders et al., 2006). Energy in each of these is described below:

- Mainline: The pipe is 65 mm PVC, at a weight of 0.74 kg/m. The embodied energy coefficient in a mainline is 120 MJ/kg. The working life of the mainline is assumed to be 40 years (Saunders et al., 2006).
- Sub-main: The sub-main is a 50 mm PVC pipe, at a weight of 0.51 kg/m. The embodied energy coefficient in a sub-main is 120 MJ/kg. The working life the a sub-main is assumed to be 40 years (Saunders et al., 2006).
- Lateral: The lateral pipe is a 16 mm low-density polyethylene (LDPE), with an embodied energy coefficient of 160 MJ/kg. The working life of the lateral is assumed to be 30 years (Saunders et al., 2006).

4.3.2 CO_2 ratio

The second criterion for sustainability is that the orchard system has to be carbon neutral or a net sink of carbon, which is identified by considering the ratio of CO_2 sequestration to CO_2-equivalent emissions. The CO_2 ratio, equal or above one, indicates that the system is carbon neutral or a net sink of carbon. The CO_2-equivalent emissions at the orchard system occur from energy consumption (both direct energy and embodied) and from the orchard soil (Figure 4.2). Carbon is sequestered in plant biomass (in growing fruit plants) and in the organic matter in the compost, which might be purchased from outside the orchard system. A portion of carbon sequestered in the plant biomass is returned back to the soil, in the form of prunings and through fine roots. This, together with the carbon that is stored in the compost, forms the carbon inputs to the orchard soil. Not all the carbon that enters the orchard soil stays there: a major portion is emitted back to the atmosphere through microbial decomposition and this adds to CO_2 emissions.

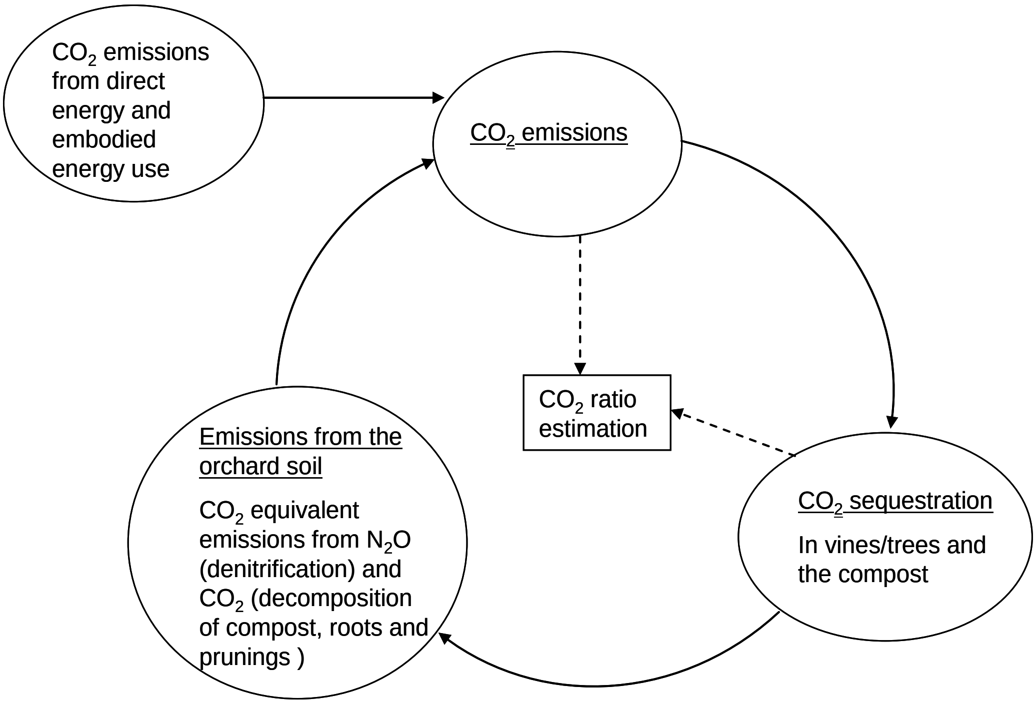

Figure 4.2 Carbon cycle of an organic orchard system.
CO_2 emissions take place from direct and embodied energy and from the orchard soil. CO_2 sequestrations take place in the vines/trees and the compost. A portion of this sequestered CO_2 is emitted back to the atmosphere from the soil. CO_2 ratio is estimated as the ratio of CO_2 sequestration and CO_2-equivalent emissions.

The CO_2 ratio is expressed as:

$$CO_2\,ratio = \frac{CO_2\,sequestration\,(kgCO_2/ha/yr)}{CO_2\,equivalent\,emissions\,(kgCO_2/ha/yr)} \qquad 4.16$$

4.3.2.1 CO_2 sequestration

The CO_2 sequestered (kg/ha/yr) is the total carbon sequestered by the kiwifruit vine or apple tree in the process of photosynthesis, expressed as CO_2, plus the CO_2 temporarily stored in compost.

$$\text{CO}_2 \text{ sequestered (kg/ha/yr)} = \text{CO}_2 \text{ sequestered in vines/trees (kg/ha/yr)} + \text{CO}_2 \text{ temporarily stored in compost (kg/ha/yr)} \quad 4.17$$

Carbon sequestration by kiwifruit and apple plants

The net carbon sequestered by a plant can be calculated as canopy photosynthesis, minus plant respiration over the growing season[15] (Greer et al., 2004). A New Zealand grown kiwifruit vine, under average orchard conditions, has been estimated to have a net carbon acquisition of 11.2 kg/vine, over a growing season (Greer et al., 2004). Multiplying the weight of carbon by 3.67[16] gives the quantity of carbon dioxide sequestered by one vine over one year (Saunders et al., 2006). For kiwifruit, CO_2 sequestered per vine per yr is 40.99 kg.

The CO_2 sequestered in the tree/vine, as presented above, is allocated to leaves, fine roots, stems and fruit in the proportion of 22:22:23:33, respectively (Kroodsma & Field, 2006). All the CO_2 sequestered in the fruit is released back to the atmosphere, once the fruit is consumed. Hence, the CO_2 sequestration in the fruit is assumed to be in a steady-state and it is not considered in the CO_2 sequestered and emitted calculations. Subtracting the CO_2 sequestered from the fruits (33% of the total CO_2 sequestered per vine/tree), the total CO_2 sequestered value per vine in leaves, fine roots and stem comes to 27.46 kg CO_2/vine/yr for kiwifruit. On average, there are 500 vines per ha. Thus, 13.7 t CO_2/ha/yr can be expected to be sequestered by an average kiwifruit orchard in New Zealand, on an annual basis.

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[15] The growing season is during spring and summer, when the plant is in an active growth period. It is assumed that no carbon dioxide is acquired outside the growing season, although losses through respiration take place, which are considered minimal.

[16] 3.67: due to the molecular weight ratio of carbon dioxide to carbon (44:12), multiplying the weight of carbon by 3.67 gives the quantity of carbon dioxide (Saunders et al., 2006).

In apple orchards, CO_2 sequestration per tree depends on tree size and planting density. A mature slender shaped 'Empire' variety of apple, grown on M-9 rootstock (semi-dwarfing rootstock) in New Zealand under intensive management, sequestered 22 kg CO_2 per tree per season (Lakso et al., 2001). The trees grafted on M-9 usually grow to about 35% of their original size (Cornell University, 2007). Assuming that the data from Cornell University are correct, an original (mature, full-sized) sized apple tree will sequester 62.85 kg CO_2/yr.

The trees grafted on M-106 (semi-dwarfing rootstock) grow between 50-70% of their original size (Cornell University, 2007; Tustin, 2007). The absolute size of the trees on these rootstocks depends on the site-specific conditions, plant spacing and tree management (Wells, 1992; Tustin, 2007). An individual tree in a semi-intensive orchard has higher vigour and grows larger than trees in an intensive orchard (Tustin, 2007). In this research, each tree in the semi-intensive orchard (up to 800 trees/ha) is assumed to grow to 70% of its original size, whilst a tree in an intensive orchard (more than 1000 trees/ha) is assumed to grow to 50% of its original size. Accordingly, the CO_2 sequestered per tree, in a semi-intensive orchard, is estimated as 43.99 kg/tree/yr. Similarly, an individual tree in an intensive orchard is estimated to sequester 31.42 kg CO_2/tree/yr.

Subtracting the CO_2 sequestered from the fruits (33% of the total CO_2 sequestered per vine/tree), the total CO_2 sequestered value per tree in leaves, fine roots and stem comes 29.47 kg CO_2/tree/yr for semi-intensive apples and 21.05 kg CO_2/tree/yr for an intensive apple orchard.

Accordingly, CO_2 sequestration/ha/yr for an apple orchard is estimated as:

*CO_2 sequestration in apple trees (kg/ha/yr) = no of trees per ha*kg CO_2 sequestration per apple tree* *4.18*

CO_2 sequestered in compost

The carbon stored in compost is proportional to the dry matter of the compost and the proportion of carbon in the dry matter. The dry matter of the compost is assumed to be 50%, based on one of the BioGro certified composts. Usually, carbon constitutes 40% of the compost dry matter. Thus, carbon stored in compost (expressed as CO_2) is estimated as:

$$CO_2 \text{ stored in compost (kg)} = \text{kg compost}*0.2*3.67 \qquad 4.19$$

4.3.2.2 CO_2 emitted

CO_2-equivalent emissions include CO_2 emissions from the use of direct and embodied energy and CO_2 and N_2O emissions from the soil, as a result of microbial decomposition of biomass and denitrification. The CO_2-equivalent emissions are expressed as:

$$CO_2\text{-equivalent emissions (kg/ha/yr)} = CO_2 \text{ emissions from direct energy (kg/ha/yr)} + CO_2 \text{ emissions from embodied energy (kg/ha/yr)} + CO_2\text{-equivalent emissions from the soil (kg/ha/yr)} \qquad 4.20$$

CO_2 emissions from direct energy

The CO_2 emissions from direct energy use are the sum of CO_2 emissions from fuel (petrol, diesel and lubricant). Farm labourers breathe out CO_2, but this is assumed to be insignificant and hence it is not considered. The CO_2-equivalent emissions from direct energy are expressed as:

$$CO_2 \text{ emissions from direct energy use (kg } CO_2\text{/ha/yr)} = \sum CO_2 \text{ emissions from individual fuel use (kg } CO_2\text{/ha/yr)} \qquad 4.21$$

CO_2 emissions from fuel use

The Intergovernmental Panel on Climate Change (IPCC, 1996) has given the base carbon dioxide emissions, associated with the consumption of diesel, petrol and lubricants, as 0.0741, 0.0693 and 0.0367 kg CO_2/MJ, respectively. To these base emission factors, an extra 0.0067 kg CO_2/MJ is added, as fugitive emissions[17] (Wells, 2001). Thus, in this study, an overall emission factor was considered to be

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[17] Fugitive emissions are those emissions that do not come from combustion but instead arise as a result of processing or transforming fuels.

0.08 kg CO_2/MJ for diesel, 0.076 kg CO_2/MJ for petrol and 0.04 kg CO_2/MJ for lubricants. The total CO_2 emissions from fuel use (by fuel type) are:

$$CO_2 \text{ emissions from fuel use (kg/ha/yr)} = \text{Fuel use (MJ/ha/yr)}* \text{ emission coefficient for the fuel type} \quad 4.22$$

CO_2 emissions from embodied energy

With every MJ of embodied energy use, a certain amount of CO_2 emissions occur. The sum of CO_2 emissions, associated with embodied energy use for *n* production inputs, gives the total CO_2 emissions from embodied energy use. The CO_2 emission coefficient for embodied energy in inputs is presented in Table 4.4. The CO_2 emissions from embodied energy use is expressed as:

$$CO_2\, embodied = \sum_n (embodied\ energy\ in\ inputs * CO_2\ emission\ \ coefficient(Table\ 4.4)) \quad 4.23$$

Table 4.4 CO_2 emission coefficient for embodied energy in inputs

Input	**CO_2 emission coefficient kg CO_2/MJ**
Rock phosphate	0.06
Agricultural lime	0.43
K	0.6
S	0.3
Mg	0.3
Biostimulants	0.08
Organic fertilisers	0.08
Mineral oil	0.08
Machinery/equipment	0.08
Agrichemicals	0.08
Electricity	0.06

Source: Wells (2001)

CO_2-equivalent emissions from the soil

CO_2-equivalent emission from soil occurs from decomposition of organic matter and nitrous oxide and it is expressed as follows:

CO_2-equivalent emissions from the soil (kg CO_2/ha/yr) = CO_2 emissions from decomposition of organic matter (kg CO_2/ha/yr) + CO_2-equivalent emissions of N_2O (kg CO_2/ha/yr) 4.24

The CO_2-equivalent emissions from the decomposition of organic matter occur through decomposition of prunings (stem and leaves), roots and compost. The nitrous oxide emissions in this study are estimated, using the Overseer® nutrient budget model, as described later in this chapter. The rate of CO_2 emissions from the decomposition of organic matter is described below under ‘changes in the soil carbon level’.

4.3.3 Changes in the soil carbon level

Change in soil carbon level is estimated as a balance between carbon inputs and carbon loss. Carbon inputs are through the addition of prunings, compost (when applied) and through decomposing roots. Carbon loss is through microbial decomposition of organic matter, relative to the carbon inputs (Paustian et al., 2000; Rustad et al., 2000).

Pruning is an important management practice in orchard crops, during which a significant amount of the previous year’s wood production is pruned and returned to the soil. The amount of pruned wood varies from crop to crop. It is estimated that 30% of the wood is pruned in orchards, whilst 50% of the wood is pruned in vineyards (Kroodsma & Field, 2006). In this study, 30% of wood was considered to be pruned in apples and 50% of wood from the kiwifruit vines. The value for kiwifruit is higher than for apples, because kiwifruit is a vigorously growing vine in which vegetative growth is stronger than in apples, therefore it has more growth to be pruned (Greer et al., 2003).

For example, the CO_2 sequestered by kiwifruit vines in leaves, fine roots and stems is 27.46 kg CO_2/vine/yr, as already described. Assuming that 50% of the carbon, sequestered in the stem, is accumulated as biomass gain in the plant framework (permanent wood) every year and the remainder of the carbon is returned to the soil in the form of prunings (50% of the stem plus all leaves) and decomposing roots[18] turnover, then the carbon input from the kiwifruit vine to the soil is estimated as 22.73 kg CO_2/vine/yr (out of 27.46 kg CO_2/vine/yr). Thus, 83% of the total carbon, sequestered by a kiwifruit vine every year, is returned to the soil. The remaining 17% constitutes a gain in the plant framework every year.

Similarly, in apple trees, 30% of the wood is pruned and the remainder accumulates in the stem, as a gain in framework. For a semi-intensive orchard, (about 800 trees/ha), 22.37 kg CO_2/tree/yr is returned to the soil, out of 29.47 kg CO_2/tree/yr. For an intensive orchard (>1000 trees/ha), 15.99 kg CO_2/tree/yr is returned to the soil, out of 21.05 kg CO_2/tree/yr. Thus, in apples, 76% of the CO_2 sequestered in the tree is returned to the soil (from leaves, stem and roots). The remaining 24% remains as a gain in plant framework.

Not all the carbon, that is inputted to the orchard soil through prunings, roots and compost application, stays in the soil. The majority of the carbon added to the soil, through these inputs, returns to the atmosphere, in the same year as CO_2 emissions. It is estimated that only 18% of carbon stays in the soil, whilst the remaining 82% is returned to the atmosphere as CO_2, within the same year. This is based on a study of a coppice-willow-bio-energy-crop in UK (Grogan & Matthews, 2002). No similar data were available specifically for orchards crops.

4.3.4 Nutrient balances

The nutrient balance is the balance between nutrient inputs and nutrient outputs, which is estimated using the Overseer® nutrient budget model. The nutrient balance is estimated for primary nutrients (N P K) and secondary nutrients (Ca Mg S) as kg/ha/yr. Nutrient inputs are from fertilisers, soil mineralisation, rainfall, and

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[18] Carbon partitioned in roots, within that year, is in the form of fine roots, which adds to the soil organic matter pool.

grass-legume understorey. Nutrient outputs are in fruit, plant and leaching and gaseous losses. The fertiliser application programme, irrigation if used, the gross yield, and the site-specific characteristics of the orchard (soil type, distance from the coast) are all required as inputs to the Overseer® model.

4.3.5 Leaching of N

Overseer® predicts the potential average annual losses of N as leaching to the ground water, based on the same information on the orchard, as described above for estimating the nutrient balance.

4.4 Analysing the orchard production systems for sustainability

Once the primary data and data from published literature are collected, the next step is to undertake the sustainability analysis. The sustainability analysis of the orchard system consists of estimating the sustainability indicators for the model organic kiwifruit and apple systems, respectively. The system is considered sustainable if all the five indicators are above the minimum threshold levels as described in section 3.5.1.

The diagram of the analytical framework for sustainability assessment is presented in Figure 4.2. Sub-model 1 (Stella® model) estimates the energy ratio, the CO_2 ratio and changes in the soil carbon level. Sub-model 2 (Overseer®) estimates the nutrient balances (N P K Ca Mg S) and leaching of N (Figure 4.2). Fertilisers used by the growers in addition to other miscellaneous information form an input to the Overseer® sub-model. Output from sub-model 2 (CO_2-equivalent emissions of N_2O from soil) becomes an input to sub-model 1 (contributes to CO_2-equivalent emissions used to estimate the CO_2 ratio).

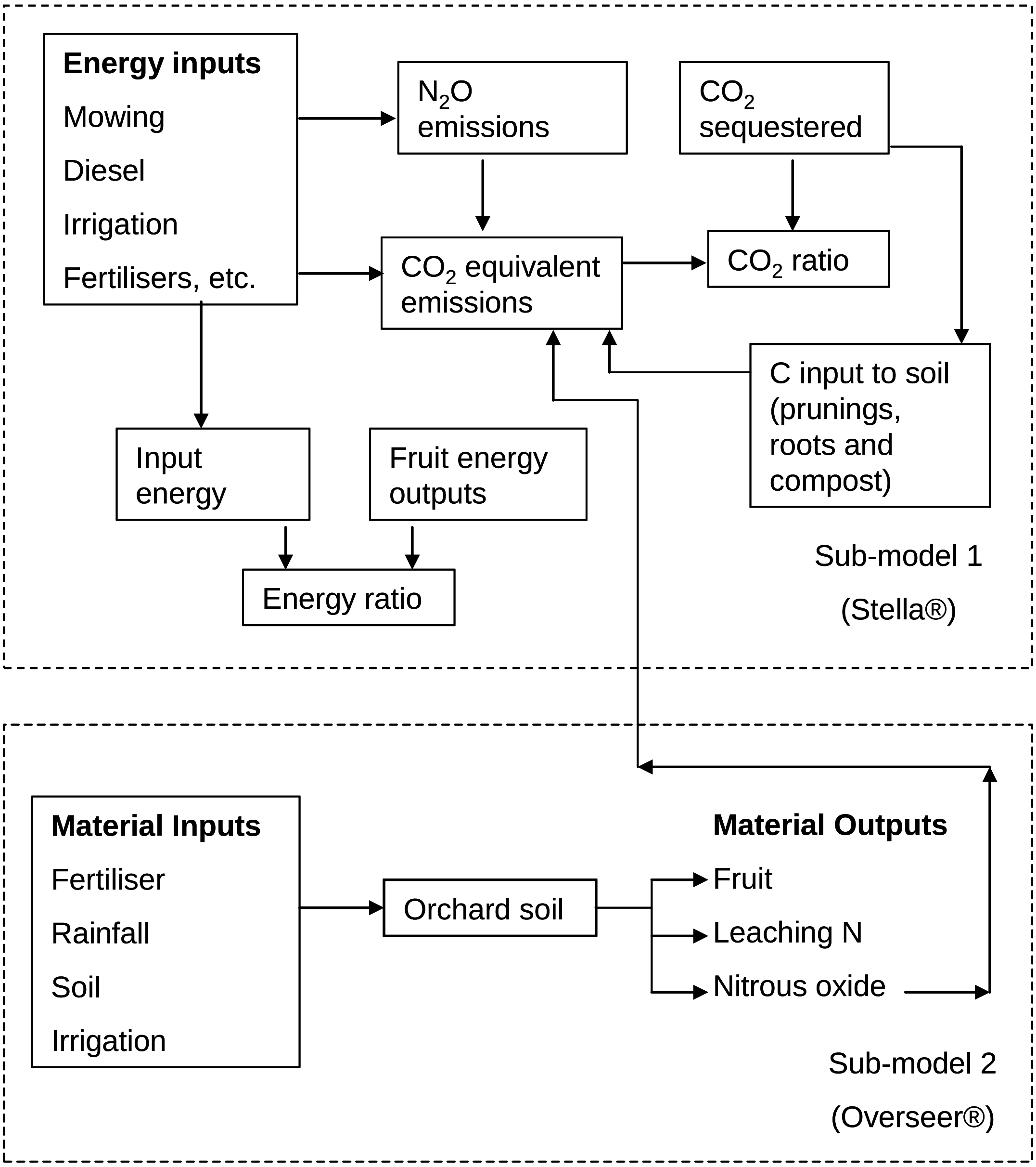

Figure 4.3 Schematic of the orchard system sustainability assessment

4.4.1 Computerised modelling environment

The use of computers has advanced the development of modelling and systems analysis (Costanza & Wainger, 1993). Computers can quickly process mathematical or logical formulations in arbitrary combinations, which have therefore widened the applicability of systems modelling. The first task in choosing software for modelling is to have a clear idea of what is being modelled and the purpose for the modelling (Bossel, 1994). The purpose in this research was to simulate the orchard production practices and their interaction with the environment, in order to estimate the sustainability indicators over one growing season. This entailed estimating energy ratio, CO_2 ratio, changes in soil carbon level, nutrient balances and leaching of N, as described earlier.

Two computer modelling software tools were used to estimate the sustainability indicators in this research. These were Stella® version 9.0.1 and Overseer® nutrient budget 2, version 5.2.4.0, both on the Windows XP® platform. Stella® is used to estimate three sustainability indicators: the energy ratio, the CO_2 ratio and the changes in soil carbon level. A model of an orchard system was created in Stella®, using symbolic icons representing flows and system variables. The symbols are connected and conversion factors are written to quantify the relationships between the model components, which are based on the primary data and the data from the published literature (Appendix III to V). Once the model is run, the sustainability indicators can be plotted in graphical or tabular form. From the indicator values, a decision can be made regarding the system's sustainability. Stella® allows exploration of multiple 'what if' questions, meaning that the effect of one or several scenarios on the model output could be tested at the same time (Odum & Odum, 2000). This is particularly relevant for this study, since one or more scenarios needed to be considered to study their effects on the sustainability indicators.

An Overseer® nutrient budget was used to predict partitioning of the nutrient inputs to the soil into respective outputs (sub-model 2 in Figure 4.2) and to estimate two sustainability indicators: nutrient balances and leaching of N, in addition to N_2O input for sub-model 1. Overseer® is a nutrient budgeting programme commonly used as an auditing tool in New Zealand, to ensure that nutrient outputs are being replaced by inputs and to see whether or not excessive amounts of nutrients, such as nitrogen, are being lost to the environment (Ledgard et al., 1999; Condron et al., 2000; Ledgard et al., 2004; MAF, 2007b). Overseer® provides average estimates of the fate of nutrients over a year, whilst ignoring year-to-year variability due to climate. The varying soil types in the different regions of New Zealand that may have different characteristics in terms of nutrient supply and N-leaching, are considered in the Overseer® nutrient budget. The nitrous oxide released from soil (expressed as CO_2-equivalents) predicted by Overseer®, becomes an input to the total CO_2 emissions in the Stella® sub-model 1 (Figure 4.2). Linking Overseer® and Stella® facilitated the estimation of the five sustainability indicators over a growing season, which would not have been possible by using either of these modelling tools in isolation.

4.4.2 Model responses to changes in model inputs

The application of the proposed sustainability assessment approach to the organic kiwifruit and organic apple systems in New Zealand will help answer the third research question posed in this research: 'How well does the proposed approach work for assessing sustainability?' Whether the model worked well for assessing sustainability was identified in two ways (Sargent, 1998). Firstly, by comparing the results of sustainability assessment of organic kiwifruit and organic apple production systems with other similar published studies; and secondly, by identifying how well the model responds to changes in model inputs. The primary data (management practices) from growers and the data taken from the published literature (model parameters) constituted the model inputs. Model response to changes in the key management practices and model parameters was undertaken through management scenario analyses and sensitivity analyses respectively, as described below.

4.4.2.1 Model responses to changes in key management practices

Various production practices are possible within official organic certification standards. Environmental impacts will vary with changes in management practices. To determine the effects of key variations in the management practices on sustainability results, a management scenario analysis was carried out. The different management scenarios were determined from the information collected from the growers and they are detailed in the kiwifruit and apple systems sustainability analysis chapters (Chapters 5 & 6), respectively. Management scenario analysis was also carried out for key scenarios identified from the literature. Management scenario analysis was undertaken using the same computer modelling tools, as those used for estimating the sustainability indicators.

4.4.2.2 Model responses to changes in key model parameters

In this research (independent of data collected from the growers) information was also gathered on various energy and matter coefficients, which were taken from the published literature. These data were used to convert primary data into appropriate energy and matter equivalents, in order to estimate sustainability indicators. The aim in undertaking the sensitivity analysis was to identify whether the model result changed, in response to the uncertainties associated with parameter values taken from the published literature. This analysis was not exhaustive in nature and no attempt was made to quantify the sensitivity of the model to all model parameters. Instead, the sensitivity analysis was undertaken for those model parameters which were either highly influential, or those that had great deal of variation and therefore they could be anticipated to have significant implications for the model results towards sustainability. Parameters were considered highly influential when they either had relatively higher embodied energy content, were used in large amounts or which directly influenced the value for sustainability indicators. Five parameters were considered to be highly influential in the model. These were: the energy content of the fruit; fruit yield; energy content in diesel; carbon sequestered in the vine/tree; and the soil CO_2 emission coefficient from the decomposition of organic matter. The energy content in the fruit and the fruit yield directly affects the output energy, and therefore the energy ratio. The carbon sequestered in vine/tree and the rate of soil CO_2 emission from decomposition of soil organic matter directly affects the CO_2-equivalent emissions and therefore the CO_2 ratio. Diesel is the main type of fuel which is anticipated to be used in large amounts for running the machinery, in the majority of the orchard production practices: therefore, diesel energy content is considered an influential model parameter. The sensitivity analysis was also carried out for those parameter values which could vary greatly. For example, the embodied energy content of organic materials such as organic fertilisers and biostimulants may vary greatly, depending upon how energy-intensive were their production processes (Edwards-Jones & Howells, 2001).

For the sensitivity analysis, model parameters were varied one at a time, whilst all the other input variables and parameters were held constant. The same computer modelling tools, used for estimating sustainability indicators, were also used to undertake the sensitivity analyses. Model parameters were hypothetically varied, to the extent that it changed the model result (e.g., from sustainable to unsustainable) and the percent variation in the model parameter was recorded. If this variation in the parameter value was within the existing uncertainty level associated with that parameter, then the model was considered sensitive to the uncertainty associated with that parameter. For example, the known uncertainty, associated with the energy content in diesel, is ±15% (Biodiesel board, 2007). If the variation of ±15% in the energy content in diesel changed the model response (from sustainable to unsustainable, or vice versa), then the model was considered sensitive to the uncertainty associated with energy content in diesel.

The lack of known uncertainties, associated with other model parameters, is considered as one of the challenges when undertaking sensitivity analysis. For example, known uncertainty for some model parameters could not be found in the literature. These included the uncertainty associated with CO_2 sequestration by vine/tree, embodied energy content of organic material and the CO_2 emission coefficient for the decomposition of organic matter. These parameters were varied individually and the percent variation in the model parameter, which was required to change the model response, was recorded. A decision was made, based on logic, as to whether variation in that parameter value, to the extent that was required to change the model response, was possible in a real situation or not. The model was considered insensitive to the variation in that parameter, if it was unlikely that the parameter value would vary to the extent that was sufficient to change the model response towards sustainability.

4.5 Summary

In this chapter, the modelling approach, using computer tools, is proposed, in order to assess the sustainability of organic kiwifruit and organic apple systems. Sustainability modelling, at the orchard systems level, is carried out in two steps. Firstly, the model orchard system is described, based on the information gathered from growers, to typify the most significant energy and material flows at the organic orchard systems level. In the second step, sustainability indicators are estimated using two computer software tools, namely, Stella® and Overseer®. The output from Overseer®, in the form of CO_2-equivalent emissions from orchard soils, forms an input to Stella®, in order to estimate the CO_2 ratio.

At a spatial level, the sustainability indicators are expressed on per ha basis and are estimated over one calendar year. Whether the differences in key management practices affect the results of sustainability is determined by carrying out management scenario analyses. Whether the uncertainties associated with key model parameters affect the results of sustainability is undertaken through sensitivity analyses.

The sustainability assessment approach presented in this chapter is applied to the organic kiwifruit and organic apple systems, the results of which are presented in the following chapters.

Chapter 5

SUSTAINABILITY OF ORGANIC KIWIFRUIT SYSTEMS

5.1 Introduction

In this chapter, the results from the application of the proposed sustainability assessment approach to an organic kiwifruit system are presented. Information, on the ways in which the organic kiwifruit system is managed, forms the first step in the systematic assessment of its sustainability. Data for orchard production practices and the inputs were obtained directly from individual growers. The range of production practices and the inputs used in these organic kiwifruit orchards are presented in the general orchard description. The model kiwifruit system, which is typical of the orchards studied, is then described. This is followed by a sustainability assessment of the model kiwifruit system, which is carried out using two computer modelling tools, as explained in the methodology. Management scenario analyses and sensitivity analyses are undertaken, in order to identify how well the model responds to changes in model inputs, as described in the methodology.

5.2 General orchard description

In this section, information on the studied organic kiwifruit orchards is provided. Data gathered from the growers is presented under orchard establishment, annual production practices and as miscellaneous information. The purpose is to describe the range of inputs used in the studied organic kiwifruit orchards, in order to derive a model system.

5.2.1 Orchard establishment

Kiwifruit is a vigorously growing vine. All the studied growers grow the Zespri Green variety of kiwifruit. One orchard also grows the Zespri Gold variety. The effective areas[19] of the orchards range from 4 to 7 ha: each orchard is divided into a number of blocks, according to the topography of the land and for ease of management. All of the orchards are owned and operated by the growers and all were originally established as conventional orchards but they have been fully certified as organic, for at least five years. The majority of the orchards have kiwifruit vines that are at full bearing age (> 7 yrs).

The orchards studied are located on predominantly loamy and well drained volcanic soils, with relatively flat to slightly rolling topography. Plant spacing varies from orchard to orchard. One orchard has a spacing of 6 m between the rows and 5 m between the vines, giving a vine population of 333 vines per ha. Plant spacing in another orchard is 5 m between the rows and 3 m between the vines, giving a vine population of 666 vines per ha. The majority of vines are spaced 5 m between the rows and 4 m between the vines, giving a plant population of 500 vines per ha. Vines in all the orchards are trained to a pergola and these vines are supported with wooden posts, timber or steel beams and galvanised wire.

Kiwifruit vines are dioecious, which means that female and male flowers are produced on different vines. Male vines are therefore required to fertilise the female vines, in order to produce fruit. The male vines constitute from 10 to 12% of the total vine population per ha.

5.2.2 Annual production practices

Production practices are broadly the same across the studied orchards. Some differences in management practices can be attributed to the soil type, local weather conditions and/or the philosophy of the grower, together with the developmental stage of the crop, such as young versus mature plantings.

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[19] The effective area is the actual area under fruit crop, also referred to as canopy area.

The kiwifruit season starts immediately after the harvest in June and continues until the end of the harvest the following year. June to May is considered as one calendar year, for organic kiwifruit. The important orchard production operations are presented in Figure 5.1.

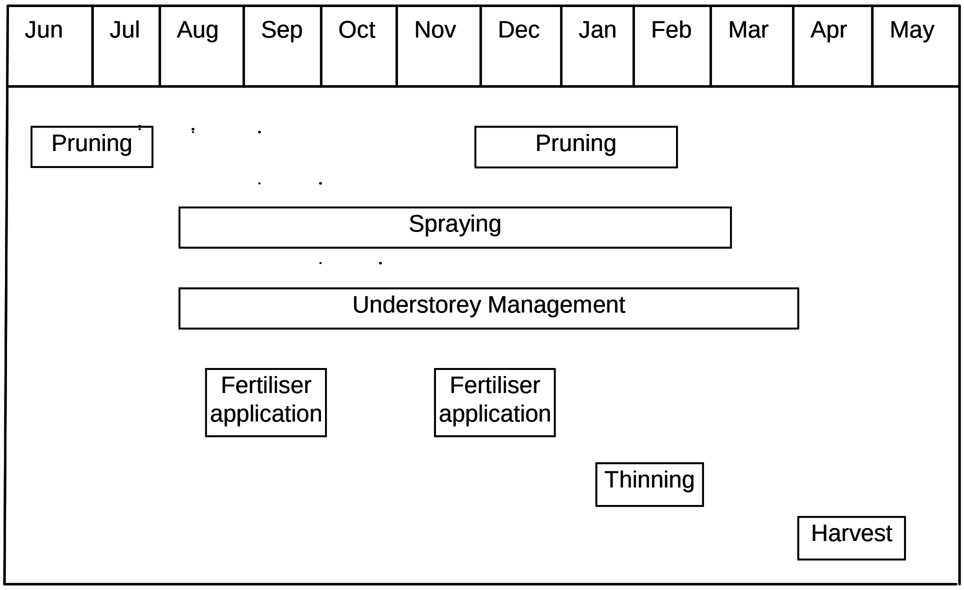

Figure 5.1 Calendar of key operations in an organic kiwifruit orchard in Bay of Plenty, New Zealand

5.2.2.1 Pruning

Pruning in all the orchards is a labour-intensive manual operation, undertaken with the aid of hand-operated pruners and loppers. It is one of the most important aspects of kiwifruit vine management and it plays a major role in obtaining consistent yields from year to year. Pruning requires the removal of the old wood, in order to allow the growth of new developing shoots. It generally occurs three times in each season. Firstly, the winter pruning is carried out in the months of June and July, followed by male pruning[20] in November. The third pruning, referred to as the summer pruning, is undertaken from November to February and this may involve a number of passes through the orchard. Prunings are left to the ground and used as mulch. The total human labour requirement, during pruning, ranges between 45-50 person-days/ha/yr.

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[20] Male pruning is the cutting back of the male branches after they have flowered.

5.2.2.2 Spraying

Spraying is accomplished either to prevent or control insect and disease infestation or to apply foliar or liquid fertilisers and biostimulants. In all the orchards, spraying starts immediately after winter pruning in August and continues through until February. Depending upon the weather conditions, it is undertaken 6-10 times annually. A tractor-drawn, PTO-driven air-blast sprayer is used for this operation.

The range of agrichemicals used in spraying is summarised in Table 5.1. All the growers apply compost tea, fish oil and seaweed spray. The commonly used insecticides are *Bacillus thuringiensis* and mineral oil, for which the amount of water per spraying ranges between 1000-1500 L/ha. In addition, organic bud-enhancers, such as pine oil or fish oil, are also used in some of the orchards, in order to increase the bud-break and therefore the yield. The time required to spray ranges from 40 to 60 min/ha.

Table 5.1 Rate of spray material application in organic kiwifruit orchards

Material and its application per 100 L water	No of sprays/yr	Application rate/ha	No of orchards to apply this spray
Fish oil; 1-2 L	1-2	10-60 L	5
Compost tea; 5-10 L	1-2	50-200 L	4
Seaweed; 1 L	1-2	15-20 L	5
Bacillus thuringiensis; 35 g	1-2	350-700	5
Mineral oil; 1 L	1-2	10-30 L	4
Bud enhancer; 6.5L	1	65 L	3

5.2.2.3 Understorey management

The understorey management includes the mulching and mowing operations. In all the orchards, the ground is covered with mixed grass-legume (predominantly clover as the legume) vegetation, between the rows and between the vines. Mulching occurs three times a year in all the orchards. This involves mulching of the pruned stem and leaves, in order to recycle nutrients back into the soil. Mulching is also undertaken to control weeds in organic kiwifruit growing.

Mowing frequency depends on the season: in winter, since the grass growth is less, it is done once every two months. In spring, mowing is required once a month, since the grass growth is faster. As the vines grow, they shade the ground and therefore mowing frequency is reduced to once in two to three months in the summer period. In all the orchards, mowing is undertaken between five and nine times a year. Understorey management is carried out with a PTO-driven mulcher or mower. The time required to mow ranges from 45 to 65 min/ha and the time required to mulch ranges from 75 to 100 min/ha.

5.2.2.4 Fertiliser application

Fertilisers are applied, in order to keep a balance between the nutrients taken up by the crop and the nutrients returned to the soil, to ensure that adequate quantities of nutrients are available to the plants, the soil fertility is maintained and losses to the environment are minimised. Differences in fertiliser use across the orchards are largely dependent upon the soil’s condition, soil and leaf test results, in addition to the personal choice of the grower.

Fertiliser application takes place mainly after the winter pruning, during the months of August/September, in order to boost the growth of new wood and to strengthen the already existing old wood. In addition, fertiliser is applied during November/December, to support developing floral shoots and to enhance fruit set. The fertilisers used in the organic kiwifruit orchards, over a typical year, are presented in Table 5.2. An annual compost application is a common practice across all the orchards. Compost application is always subcontracted and it is carried out by using a compost spreader. Four of the growers usually purchase compost from commercial suppliers, whilst one grower prepares compost on-site, using the raw material found within the orchard.

Application of magnesium-based fertilisers, such as kieserite is common across the orchards. Phosphorus, as rock-phosphate, is applied to three orchards, at a rate of 200-300 kg/ha. Lime is commonly used as a soil conditioner, in order to raise soil pH across all the orchards, at the rate of 300-500 kg/ha. The time required for fertiliser application ranges from 30 to 45 min/ha. Fertilisers are applied between 3-4 times in a year.

Table 5.2 Rate of fertiliser application in organic kiwifruit orchards

Fertilizer	**Application rate/ha/yr**	**No of orchards that applied**
Compost	6-10 t	5
Potassium sulphate	150-200 kg	4
Kieserite	100-300 kg	5
Patent kali	250 kg	1
Rock phosphate	200-300 kg	3
Fish meal	200-300 kg	2
Agricultural lime*	300-500 kg	4

** used as a soil conditioner*

5.2.2.5 Thinning

The objective of fruit thinning is to reduce the number of fruits per vine, in order to increase fruit size, distribute the fruit equally on the branches and remove undesirable fruit. Hand thinning is carried out with the help of contracted labourers, from December to mid-February. The labour requirement for thinning ranges between 15-20 person-days/ha/yr.

5.2.2.6 Harvesting

Harvesting is undertaken once a year, during April and May. Individual fruit is picked by hand, put into wooden bins and brought to a central place. The wooden bins are transferred by a forklift onto trucks for transport to the pack-house. The labour requirement for harvesting ranges between 12-15 person-days/ha/yr.

5.2.3 Miscellaneous information

Further information relating to the orchard includes the yield data, the transport of fruit to the pack-house, the machinery and equipment held in the orchard and the description of the irrigation and frost protection systems, if used.

Yield

The gross yield (picked fruit) across the orchards ranges from 5500 to 6500 trays. This is equivalent to 19.3 to 22.8 t/ha (one tray is approximately 3.5 kg). All picked fruit is transported to the pack-house.

Transport

Medium to large trucks (20 t tare-weight[21]) are used to transport fruit from the orchard to the pack-house. Pack-houses are located from 8 to 40 km from the orchards. Similar sized trucks transport compost from 80-100 km, in order to reach the orchard.

Human labour use

The total labour use across the orchards is estimated to be 65-75 person-days/ha/yr which includes the labour requirement in carrying out the various production practices, preparing sprays, pest monitoring and obtaining organic certification.

Machinery and equipment held at the orchards

The list of machinery and equipment used on the orchards is presented in Table 5.3. All growers own at least one tractor, a sprayer, a mulcher and a mower.

Table 5.3 List of machinery/equipment held at the organic kiwifruit orchards

Item	Number of items	Specifications	No of orchards the item is held
Tractor	1-2	55-65 hp	5
Sprayer	1	1000-1500 L	5
Mulcher *	1	400-500 kg	5
Mower *	1	400-500 kg	5
Trailer *	1-2	350-500 kg	5
Motorbike	1	200 kg	1
Spreader*	1	125-200 kg	4

* *The weight of farm implements is an estimate by the growers*

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[21] Tare-weight is the empty weight of the vehicle.

Irrigation and frost fighting

Only one of the five orchards has an under-tree, micro-sprinkler irrigation system, whilst the rest depend on rainfall for the orchard's water requirement. The particular orchard that uses irrigation is located on the light, free-draining pumice soils of the Eastern Bay of Plenty. These soils are drought-prone and irrigation is mainly applied in the spring and summer seasons.

This same orchard also has a frost protection system installed, since the area is prone to the occurrence of frosts. Frost fighting operations are aimed at avoiding damage to the crop, when the temperature falls below 0^0 C, during the sensitive stages of crop growth. The frost protection system, used in this orchard, is a two-blade wind-machine that runs on diesel, which is used for an average of 40 hours in any one season. The remainder of the growers did not use frost fighting equipment, since they believe that frost is not a threat to their crops, due to the site-specific advantages of their orchards.

5.3 The model organic kiwifruit system

The general orchard description forms the foundation from which a model organic kiwifruit system, which is typical of the studied orchards, is derived. The model organic kiwifruit system is a 5 ha certified organic orchard planted with Zespri Green variety. The plant population is 500 vines per ha, with a spacing of 5 m between rows and 4 m between vines. There is a wooden post and an overhead wooden cross-arm for each vine. Each vine is supported by eight wires of 5 m, giving a total of 40 m galvanised wire per vine.

The model organic kiwifruit system is managed and worked by the owner, with casual or contract workers hired for pruning, picking, harvesting, thinning, shelter-trimming and transporting the fruit to the pack-house. Human labour is used for carrying out various operations, such as running the machinery, making spray preparations, pest monitoring, pruning, thinning, harvesting, and so on. The total labour use is estimated to be 70 person-days/ha/yr. The model kiwifruit system is not irrigated and it does not have to use a frost protection system. The pack-house is located 15 km from the orchard. The gross yield of the model kiwifruit system is

6000 trays/ha (21 t/ha). A 45 kW tractor is used for spraying, fertiliser application, harvesting, mulching and mowing. Compost is purchased from a commercial supplier located100 km away from the orchard.

The machinery and equipment used in the model organic kiwifruit systems are presented in Table 5.4.

Table 5.4 Machinery and equipment held at the model organic kiwifruit system

Item	**Specifications**
Owner held	
Tractor	45 kW (60 hp)
Trailer	500 kg
Mower	500 kg
Mulcher	500 kg
Sprayer	500 kg
Spreader	125 kg
Contracted*	
Shelter-trimmer	80 kW
Forklift	45 kW
Truck	20 t
Compost spreader	1400 kg

Source: Obtained from interviews with growers
Note: mass in kg represents the empty (tare) weight of the machinery/equipment
** assumed to work over 200 ha in one year, with a service life of 15 years, except the truck, which is assumed to work over 300 ha/yr.*

The spraying programme of the model organic kiwifruit system is summarised in Table 5.5.

Table 5.5 Spraying programme for the model organic kiwifruit system

Material and its application rate per 100L water	Water used L/ha	Number of passes in a year	Total material kg or L/ha/yr
Fish oil; 2L	1500	2	60 L
Compost tea; 10L	1000	2	200 L
Seaweed; 1L	1500	2	30 L
Bacillus thuringiensis; 35g	1000	2	1.06 kg
Mineral oil; 1L	1500	2	30 L
Organic bud enhancer; 6.5L	1000	1	65 L
Total no of sprays*		7	

** Compatible materials were mixed together and hence the total number of sprays in one year is lower than the sum of the number of passes*

The fertilisers and their rates of application for the model kiwifruit system are presented in Table 5.6.

Table 5.6 Fertiliser application programme for the model organic kiwifruit system

Material	Rate/ha/yr
Compost	8 t
K	82 kg
Mg	54 kg
S	105 kg
Agricultural lime	500 kg
Rock phosphate	250 kg

In Table 5.7, the amount of fuel used for carrying out the various operations for a model organic kiwifruit system is presented. The fuel used per hr is estimated as per Martin (2003), as described in the methodology (equation 4.6).

Table 5.7 Fuel consumption of the model organic kiwifruit system

Operation	**Fuel use L/hr**	**Work rate hr/ha**	**Fuel use L/pass**	**No of passes/yr**	**Total fuel L/ha/yr**
Spraying	9.45	0.75	7.08	7	50
Mowing	9.45	0.92	8.69	6	43
Mulching	9.45	1.50	14.17	3	43
Fertiliser spreading	9.45	0.50	4.72	4	19
Hedge trimming	21.00	0.50	10.50	1	11
Harvest tractor	9.45	2.0	18.90	1	19
Forklift	11.80	0.50	11.80	1	6
Compost app.*	-	0.50	4.00	1	4
Total					**194**

**Fuel required for compost spreading is based on the growers' estimate.*

Fuel consumption per ha per year is the sum of fuel consumption for individual operations and inputs. The total diesel requirement of the model kiwifruit system is 194 L/ha/yr (Table 5.7). The lubricant requirement is estimated to be 7.7 L/ha/yr (4 L lubricant/100 L fuel[22]).

5.4 Sustainability analysis of the model organic kiwifruit system

Sustainability indicators for the model organic kiwifruit system are estimated, using the information on the orchard production practices and the parameters derived from the literature, as described in detail in Chapter 4. The schematic representation of the model organic kiwifruit system and the equations in Stella® are presented in Appendix III. Sustainability indicators include the estimation of the energy ratio, CO_2 ratio, changes in soil carbon level, nutrient balances and leaching of N.

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[22] Lubricant requirement was estimated by the growers to be 4 L for every 100 L diesel/petrol used.

5.4.1 Energy ratio

The energy output/input ratio of the model organic kiwifruit system is 1.57, meaning that the model organic kiwifruit system is efficient in converting energy in inputs into fruit energy output. The energy use of the model organic kiwifruit system is 34.17 GJ/ha, and the yield of the kiwifruit system is 21 t/ha. In energy terms, the fruit energy output equates to 53.55 GJ/ha.

The energy requirements for the various operations and inputs are presented in Table 5.8. Spraying is the most energy consuming operation, contributing 20% of the total energy inputs, followed by compost making and application (Figure 5.2). Diesel is the most energy-intensive input (2.31 GJ/ha) within the spraying operation, contributing to 30% of the energy in spraying. The lower energy consuming input of the model organic kiwifruit system is the use of lime, lubricants and shelter-trim, which contribute not more than 2% of the total energy use. The energy expended in human labour is the only non-renewable energy source and it contributes 4% of the total energy use.

Table 5.8 Energy use and CO_2 emissions from individual operation/processes of the model organic kiwifruit system

Operations and inputs	**Energy use MJ/ha/yr**	**CO_2 emissions kg/ha/yr**
Mowing	4,251	340
Mulching	3,771	302
Harvesting	1,920	151
Vine support	1,769	142
Lime use	300	215
Human labour use	1,281	NA
Lubricant use	374	15
Shelter-trimming	733	59
Fertiliser use	4,000	337
Compost making and application	4,662	373
Spraying	7,057	565
Transporting	4,056	324
CO_2 equiv. N_2O from Overseer®	NA	249
CO_2 from the soil	NA	14,160
Total	**34,174**	**17,232**

NA= not applicable

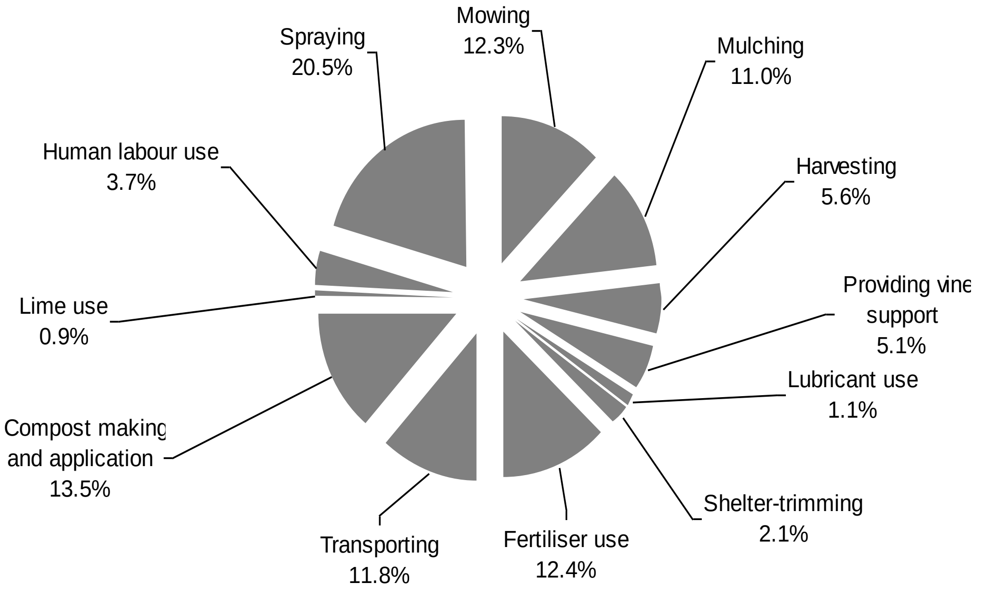

Figure 5.2 Energy use in the model organic kiwifruit system

5.4.2 CO_2 ratio

The CO_2 ratio of the model kiwifruit system is 1.13. A ratio of more than one suggests that a model kiwifruit system is a net sink of CO_2-equivalent emissions.

The release of CO_2-equivalent emissions from each operation and process is presented in Table 5.8. The release of CO_2-equivalent emissions from the use of direct and embodied energy are 2.83 t CO_2/ha/yr. Soil is the major source of CO_2 emissions to the atmosphere contributing 82% of the total emissions (14.40 t CO_2/ha/yr). The total CO_2-equivalent emissions from energy use and from the soil are 17.23 t CO_2/ha/yr. The total amount of carbon sequestered/ha in the kiwifruit vines is 13.73 t CO_2/ha/yr. Carbon, which is temporarily stored in the compost, is 5.87 t CO_2/ha/yr (the temporary nature of carbon sequestration in the compost is addressed by considering its release from the soil, as described in the methodology). Total carbon sequestration in terms of CO_2 sequestration per ha is 19.60 t CO_2/ha/yr. As the sequestration of carbon is higher than the release of carbon, the model organic kiwifruit system is a net sink of CO_2-equivalent emissions.

5.4.3 Changes in the soil carbon level

It is estimated that 846 kg C/ha/yr is sequestered in the model organic kiwifruit orchard soil from prunings and roots and the application of compost.

Soil carbon sequestration is estimated as the balance between the carbon inputs to the orchard soil through management practices and the loss of carbon from the orchard soil to the atmosphere, as a result of microbial decomposition relative to the soil carbon inputs, as described in the methodology.

It is estimated that 3096 kg of carbon are inputted to the soil every year from the vines/ha/yr. Carbon is also added to the orchard soil through the application of compost. From 8 t of compost applied, it is estimated that 1600 kg/ha of carbon are added to the orchard soil every year (0.2% of compost fresh weight is carbon). Thus, a total of 4,696 kg/ha of carbon are added to the orchard soil each year from the vines and the compost.

However, not all the carbon entering the soil remains in the soil. A large portion is lost to the atmosphere, during the same year, due to microbial respiration. It is estimated that from 4,696 kg/ha of carbon, 3,850 kg carbon are lost to the atmosphere as $CO_{2.}$

5.4.4 Nutrient balances

The nutrient balances are estimated using the Overseer® nutrient budget, as described in the methodology. The fertiliser inputs of the model organic kiwifruit system and the site-specific characteristics of the orchard form an input, in order to estimate nutrient balances.

The nutrient balances predicted by Overseer® suggest that the primary nutrients N P, and K and the secondary nutrients, such as Ca, Mg, and S, are adequately supplied, since the inputs exceed the outputs (Table 5.9). This suggests that there is no threat of these nutrients are mined from the orchard soil.

Table 5.9 Nutrient balances of the model organic kiwifruit system kg/ha/yr (from Overseer®)

	N	P	K	S	Ca	Mg
Inputs	90	108	106	104	247	74
Outputs	50	10	94	99	60	53

5.4.5 Leaching of N

The nutrient balances suggest that N is supplied in surplus amounts than that which is exported. Overseer® predicts leaching losses of approximately 11 kg N/ha/yr. The level of N, which occurs as leaching in the water, is estimated from Overseer® to be 1 mg N/L. This level is considered as a potential threat to the aquatic ecosystem from eutrophication, although it is considered safe for human health.

The grass-legume understorey was a significant factor for causing N surplus and N-leaching losses, at levels that can be a potential threat of eutrophication. However, Overseer® predicted that in the absence of grass-legume understorey, the N-leaching did not exceed the threshold level of 0.5 mg M/L. In addition, the absence of understorey meant that inadequate N is supplied to meet the crop's requirement.

5.5 Model responses to changes in key model inputs

As described in the methodology, management scenario analyses and sensitivity analyses are undertaken, in order to identify how well the model for sustainability assessment responds to changes in the model inputs of the organic kiwifruit system, respectively. These are described below.

5.5.1 Management scenario analysis of the model organic kiwifruit system

The model kiwifruit system, described in section 5.3, represents a 'typical' orchard. However, it was observed that management practices varied across the studied orchards. For example, one grower made compost on-site, rather than purchasing it from commercial suppliers. Of the five orchards, one grower used irrigation, in addition to frost fighting. To determine the effect of varying key management practices on sustainability indicators, the following management scenarios were simulated, using the same computer modelling tool as described in the methodology. The different scenarios in management analyses are described below.

Scenario 1: What if the grower decides to make compost on-site?

If the grower decides to prepare compost in the orchard, then he/she is saving on energy used in transporting the compost from the supplier. It is assumed that it takes the same amount of energy for compost preparation, whether the compost is made on-site or made by the commercial supplier. Therefore, the embodied energy in compost preparation is kept unchanged in this scenario. A lower amount of compost is applied when the compost is prepared on-site (6 t/ha/yr, as compared to 8 t/ha/yr when the compost is purchased), due to constraints on the availability of raw material in the orchard. When the compost is prepared on-site, prunings are collected and composted, together with other organic material, such as grass from the un-cropped section and shelter-trimmings. In the base scenario, prunings and other organic material, such as grass from headlands and shelter-trims are mulched back to the soil, rather than being composted.

In Table 5.10, the scenario in which compost is made on-site is compared with the base scenario, in which compost is purchased. The energy ratio and the CO_2 ratio are increased, when the compost is prepared on the orchard, rather than when the compost is purchased from outside, due to the energy used in transporting the compost is saved. Although the CO_2 ratio is increased, a lower amount of carbon is sequestered in the orchard soil, when the compost is prepared on-site. This is logical because additional organic matter (and subsequently carbon) is added to the orchard from outside the orchard, when the compost is purchased, compared to when the compost is prepared using only the organic material from the orchard.

Table 5.10 Comparison between compost purchased and that prepared on-site in the model organic kiwifruit system

Sustainability indicator	**Compost purchased (base scenario)**	**Compost prepared on-site**
Energy ratio	1.57	1.75
CO_2 ratio	1.13	1.14
Changes in the soil carbon level (C sequestration kg/ha/yr)	846	559

Scenario 2: What if the orchard location requires irrigation, in addition to a frost protection system?

Irrigation is not normally required for the commercial growing of organic kiwifruit. However, irrigation is used in one of the orchards. This particular orchard is located on light, free draining pumice soils in the Eastern Bay of Plenty, which are prone to drought, especially during spring and summer (MAF, 2006a). Therefore irrigation is required for the commercial production of kiwifruit in this orchard. The type of irrigation system used is an under-tree micro-sprinkler. This same orchard is also prone to the occurrence of frosts. A frost protection system has been installed in this orchard, in order to minimise the fruit losses to frost injury. In this orchard, a two-bladed wind machine is used for an average of 40 hours annually.

The embodied energy of the irrigation system is a combination of the embodied energy in well drilling and the embodied energy in the manufacture of pumps and pipes, as described in the methodology. It is estimated that the well is at a depth of 30 m and a pump of 40 kg is fitted to the well. In one ha, there are 20 rows, each of which is 100 m long. With this information, the embodied energy in the irrigation system is estimated to be 1272 MJ/ha/yr. Details of the embodied energy estimation in the model organic kiwifruit irrigation system are described in Appendix VI. The grower did not know the electricity usage during irrigation, since the electricity meter was shared and therefore the electricity usage for irrigation was taken from previous studies pertaining to kiwifruit systems, which is 895 kWh/ha/yr (Barber & Pellow, 2005). The embodied energy in the frost protection system is estimated to be 2133 MJ/ha/yr (Appendix VI).

Irrigation has been considered to increase yields, compared to non-irrigated kiwifruit in New Zealand orchards (Miller et al., 1998). A similar pattern was observed in this particular orchard, which formed part of the study, such that it also recorded the highest yield amongst all the orchards studied (6500 trays/ha).

When both, an irrigation system (895 kWh/ha) and a frost protection system (40 hr) are used for the high yield (6500 trays), the energy ratio is lowered from 1.57 to 1.03 and the CO_2 ratio from 1.13 to 1.06. This means that installation of irrigation and frost fighting lowered the energy ratio and the CO_2 ratio. However, the system still remains marginally energy efficient and a net sink of CO_2.

Scenario 3: What if the grower applies fish meal

Some growers apply fish meal (250 kg/ha/yr), instead of rock phosphate, which is a source of both nitrogen and phosphorus. With this scenario (and keeping all the other inputs constant), the energy ratio lowers from 1.57 to 1.55. Fish meal supplies additional nitrogen, which increases N-leaching losses from 1 mg/kg/yr to 2 mg/kg/yr.

5.5.2 Sensitivity analysis of the model organic kiwifruit system

The purpose for undertaking a sensitivity analysis is to identify whether or not the model results change, in response to the uncertainty associated with key model parameters. The results from the sensitivity analysis are presented in Table 5.11. The model is insensitive to the uncertainty associated with fruit energy content, energy content in diesel, fruit yield, the embodied energy in organic materials and CO_2 sequestered per individual kiwifruit vine.

Sensitivity analyses suggest that the model results will change, only if the fruit energy content lowers from 2.5 to 1.7 MJ/kg. This result means that insofar as the fruit energy content remains above 1.7 MJ/kg, energy use of the model organic kiwifruit will be efficient.

The growers expressed the possibility of variation in yield up to 5 t/ha/yr. Sensitivity analyses suggests that the model results will change only when the yield reduces by 7.5 t/ha/yr or more. Thus, a variation in yield by 5 t/ha/yr will not have any effect on the model results.

The embodied energy in organic materials was assumed to be 5 MJ/kg in this research, following Helsel (1993). Sensitivity analyses suggest that the model response changes only when the embodied energy content of the organic materials increases from 5 to 60 MJ/kg.

The energy content in diesel is considered to be 46.7 MJ/L, following Wells (2001). The model response changes only when the energy content in diesel increases to 145 MJ/L. Insofar as the energy content in diesel does not increase from 46.7 to 145 MJ/L or above, the results remain the same.

An average kiwifruit systems sequesters about 13.7 t CO_2/ha/yr (Greer et al., 2004). Sensitivity analyses suggests that the system is carbon neutral only when the sequestration of the individual kiwifruit vine is as low as 15 t CO_2/ha/yr (which is 7.5 t CO_2/ha/yr with 500 vine/ha). Hence, insofar as the CO_2 sequestered in an individual vine does not lower to 15 kg, the model results will not change.

The only parameter, to which the model results are sensitive, is the variation in CO_2 emission coefficient from the decomposition of organic matter. This parameter value was taken from Grogan and Matthews (2002) and it was 82% relative to the soil carbon input. If this parameter value increases from 82% to 95%, then the CO_2 ratio lowers below one and the organic orchard system is not a sink of CO_2. This means that insofar as less than 95% of the carbon that enters the orchard soil is lost, the organic orchard system remains CO_2 sink.

Table 5.11 Model responses to variation in parameters in the model organic kiwifruit system

Model parameter	Original value*	New value to change the model response**	Uncertainty or the range in variation	% variation from the original value	Sensitive/ insensitive
Fruit energy content MJ/kg	2.5	1.7	-	32	insensitive
Yield*** t/ha/yr	21	13.5	5 t/ha/yr	36	Insensitive
Embodied energy in organic materials MJ/kg	5	60	-	1100	insensitive
Energy content in diesel MJ/kg	46.7	145	±15%	210	insensitive
CO_2 sequestered per kiwifruit vine kg/yr	27.46	15	-	45	insensitive
CO_2 emission coefficient from soil organic matter decomposition %	82	95	-	16	sensitive

* *The value taken from published literature, as described in the methodology chapter*
*** Hypothetical value of the respective parameter to change the sustainability result*
**** The growers estimate an average variation in yield of 5 t/ha/yr*
- Uncertainty unknown

5.6 Summary

In this chapter, a sustainability assessment of the organic kiwifruit system was undertaken. The first step was to derive a model organic kiwifruit system, which was typical of the studied orchards. This description of the model organic kiwifruit system was then used in conjunction with the data from the published literature, in order to estimate sustainability indicators using computer modelling tools. Management scenario analysis and sensitivity analysis were carried out, in order to see the effect of variation in management practices and model parameters on sustainability indicators, respectively.

In summary, the sustainability indicators suggested that the model organic kiwifruit system was efficient in the conversion of input energy into fruit energy output. All the CO_2-equivalent emissions were offset, without any release into the atmosphere and hence the model organic kiwifruit system was a net sink of CO_2. The amount of carbon sequestered to the orchard soil, through the application of prunings and compost, was 846 kg/ha/yr. The nutrient balances were positive. However, N-leaching level from the orchard system could be a potential threat of eutrophication. Orchard understory was a significant factor to cause N surplus and N-leaching. However, maintaining the orchard without this understory meant that N was not adequately supplied to meet crop requirements.

The orchard, in which irrigation and frost fighting were used, lowered the energy ratio and CO_2 ratio but it managed to remain energy efficient and a net sink of CO_2. The CO_2 ratio was higher when compost was prepared in the orchard. However, the amount of carbon added to the system was lower than when the compost was purchased. The sensitivity analysis suggested that the model was insensitive to the uncertainties, in most of the parameters under investigation, except for the CO_2-emission coefficient from the decomposition of soil organic matter.

Chapter 6

SUSTAINABILITY OF ORGANIC APPLE SYSTEMS

6.1 Introduction

The results of the application of the proposed sustainability assessment approach to the organic apple systems are presented in this chapter. Management practices and production inputs play important roles, which affect the state of the environment. Information on the way in which organic apple systems are managed, therefore, forms the first step in the systematic assessment of their sustainability. The range of production practices and the inputs used in organic apple orchards are presented in the general orchard description. From this information, two model organic apple systems are derived, the semi-intensive and the intensive system respectively. Sustainability assessments of the two model apple systems is undertaken using computer modelling tools, Stella® and Overseer®, as described in the methodology. Management scenario analyses and sensitivity analyses is undertaken, in order to identify how well the models respond to changes in model inputs, as described in the methodology.

6.2 General orchard description

In this section, the range of information on organic apple orchards is described. The information gathered from the growers is provided under orchard establishment, annual production practices and as miscellaneous information. This information will form the basis on which to derive two model organic apple systems.

6.2.1 Orchard establishment

A mixture of apple cultivars is grown in all the studied orchards. These include Royal Gala, Braeburn, Fuji, Pacific series, Cox’s Orange Pippin and Granny Smith and other cultivars, to a lesser extent. The effective orchard area varies from 10 ha to 65 ha. Three of the orchards crop a relatively smaller area (<15ha) and they are semi-intensive (relatively lower number of apple trees per ha) and are owner operated, whilst the remaining two are relatively intensive (relatively higher number of trees per ha) larger (>50ha), corporate[23] undertakings. All the orchards were established as conventional orchards and they have been operated as certified organic orchards for at least four years. In all the orchards, most of the area is planted with apple trees, which are at full-bearing age (>10 years).

The orchards are located on alluvial soils in the 'Heretaunga Plains' region in the North Island of New Zealand, the topography of which is relatively flat to slightly rolling. The predominant rootstock is MM-106, with M-793 present to a lesser extent. Tree population varies from orchard to orchard, depending upon the spacing between the rows and trees. The rows are spaced from 4 to 5m apart and the distance between the trees ranges from 2 to 2.5m, giving a plant population of 800 to 1250 trees per ha. Trees in one orchard do not require support, whilst trees in the remaining four orchards are supported by wooden posts and two layers of galvanised wires.

6.2.2 Annual production practices

The calendar of operations is similar across all the orchards. The apple production season begins just after harvest and continues through the following year's harvest, all year round. June to May is considered as one calendar year for apple growing. The important orchard production practices are presented in Figure 6.1.

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[23] Corporations have played an important role in increasing the area under organic apple production in Hawke's Bay (Reider, 2007). Corporations either take over and manage already existing orchards, or support growers in the transition to organics by providing information, conversion price premiums, and a link to international markets.

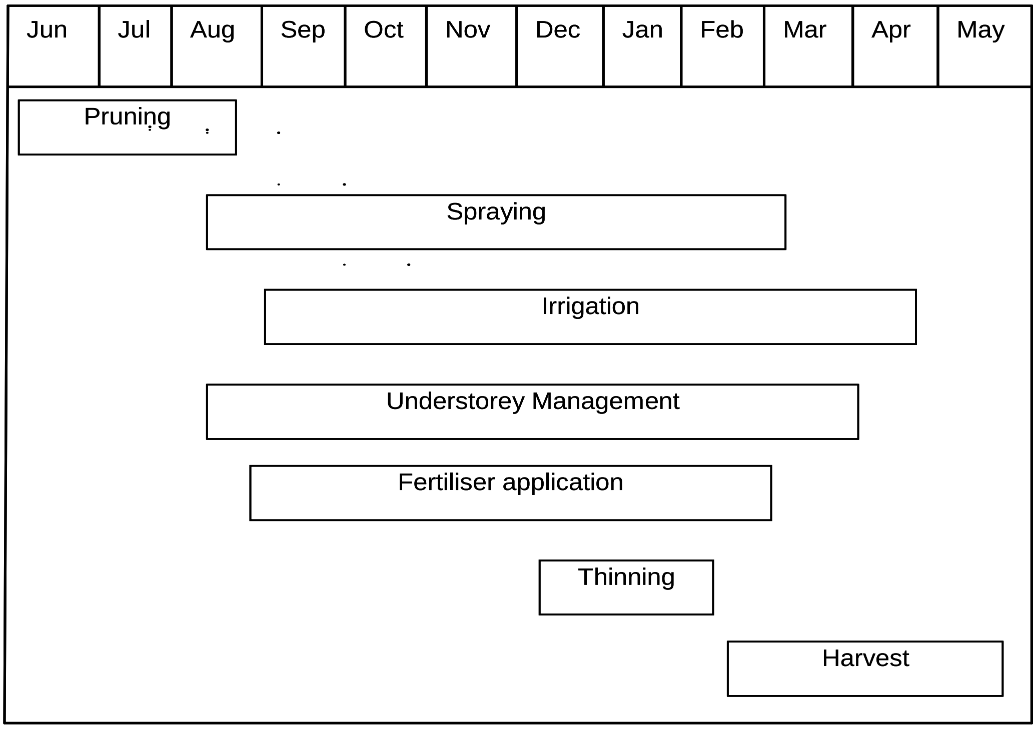

Figure 6.1 Calendar of key operations in an organic apple orchard in Hawke's Bay, New Zealand

6.2.2.1 Pruning

Pruning consists of pruning apple trees after harvest, in order to remove the old wood and make way for new growth to bear fruit in current and future crops. Pruning is also undertaken with the aim of assuring access to light for the developing wood and fruit. In this way, the fruit can develop optimally and the proportion of fruit that reaches the export market (pack-out) is higher, than for the trees without pruning. Pruning in all the orchards is done by hand, with the aid of either machine-operated hydraulic ladders (hydra-lada) or aluminium ladders for elevation.

In all the orchards, prunings are left on the orchard floor to be mulched, in order to recycle the nutrients into the soil. The other type of pruning is that of shelter trees, which is commonly called shelter-trimming and is usually done once a year. Shelter trimmings are also mulched on the orchard floor, in order to recycle nutrients.

6.2.2.2 Spraying

The spraying operation is mainly aimed at preventing or controlling a wide range of pests and diseases. Insecticides are used to fight codling moth, leaf roller, bronze beetle, scale and aphids. The main disease of concern is black spot, followed by powdery mildew. In two orchards, calcium sprays are typically used to minimise the effect of the bitter-pit, which is a serious storage disorder in apples, especially in the susceptible cultivar Braeburn. Magnesium sulphate, compost tea and seaweed sprays are applied in the form of foliar and liquid fertilisers. All the orchardists use lime sulphur, copper and elemental sulphur as fungicides. *Bacillus thuringiensis*, codling moth granulosis virus, and macrocyclic spinosad are used as biocontrol agents. Compost tea, molasses and seaweed spray are used to enhance soil health.

The total numbers of spray applications vary from 28 to 42 per season, depending upon the compatibility of product mixtures, the concentration of spray materials, weather conditions and the planting density. Generally, intensive orchards, which have high-density cropping, have a greater number of sprays than the semi-intensive orchards, which have a relatively lower number of trees per hectare. This might occur because of the lower air movement in the intensive orchards, which harbours favourable conditions for disease occurrence (Daly, 1994b). A spray volume of 2000 L/ha is commonly used across all the orchards, when using lime sulphur, copper and elemental sulphur as fungicides. A spray volume of 500-1000 L/ha is common for compost tea application, seaweed spray and molasses. The spray volume for *Bacillus thuringiensis* is 200 L/ha, which is administered aerially to control leaf roller. The range of spray materials and their rate of application in the orchards studied are presented in Table 6.1. The time required to carry out spraying, using a 2000 L PTO-driven sprayer, ranges between 35 to 45 min/ha, depending upon the number of rows, the work rate of the spraying operators and the orchard’s layout and topography.

Table 6.1 The range of spray materials and their rate of application in organic apple orchards

Material and its application per 100 L water	No of sprays	Rate/ha	No of growers who applied
Mineral oil; 2 L	1-2	30-80 L	3
Copper hydroxide; 25-32 g	7-10	3.5-6.4 kg	5
Lime sulphur; 1-2 L	6-22	100-320 L	5
Spinosad; 6 ml	2-4	0.24-0.48 L	5
Codling moth granulosis virus; 5 ml	1-8	20-600 ml	5
Bacillus thuringiensis; 50 g	1-5	0.2-1 kg	3
Elemental sulphur; 100 g	2-5	4-12 kg	5
Compost tea; 10 L	1-2	100-200 L	2
Calcium; 75 g	1-2	0.75-1.5 kg	2
Magnesium sulphate; 100 g	1	1.5 kg	1
Seaweed spray; 1-2 L	1-2	20 L	2
Molasses; 1-2 L	1-2	20 L	3

6.2.2.3 Fertiliser application

The amount and frequency of fertiliser application depend on leaf and soil test reports, soil condition, management practices and the philosophy of the grower. Compost purchased from a commercial supplier is applied once every four years, in all the orchards studied. Lime is applied annually as a soil conditioner in all the orchards, at a rate of 250-500 kg/ha (Table 6.2). Rock phosphate is applied at a rate of 300-500 kg/ha. Some orchards also apply kieserite and blood and bone.

The time required for applying fertiliser ranges from 35 to 45 min/ha. Fertiliser application takes place three to four times in a year after winter pruning in August/September and it may continue until February.

Table 6.2 The range of fertilisers and their rate of application in organic apple orchards

Material applied	Rate kg/ha/yr	No of growers who used
Blood and bone	500-600	2
Kieserite	200-250	3
Rock phosphate	300-500	4
Agricultural lime	250-500	5
Biophos	300-500	2

6.2.2.4 Understorey management

Understorey management includes mowing and mulching operations. In all the orchards, the ground is usually grassed-down permanently with mixed grass-legume (predominantly clover as the legume) vegetation between the rows and between the trees. Mowing frequency depends on the weather and mowing is usually carried out five to eight times a year, depending on sward growth. Mulching of prunings is undertaken in all the orchards once a year, in order to recycle the nutrients from prunings and shelter-trimmings. Weeds were controlled through mulching and mowing operations. Understorey management is carried out with a PTO-driven mulcher or a mower. The time required to carry out mowing ranges from 45 to 60 min/ha and the time required for mulching ranges from 120 to 150 min/ha.

6.2.2.5 Thinning

The objective of fruit thinning is to reduce the number of fruit per tree, in order to increase fruit size and minimise biennial bearing. Thinning also allows fruit to be evenly distributed on the branches. In all the orchards, hand thinning using contracted labourers is carried out. All the orchards require either aluminium ladders or a hydra-lada (machine-operated ladder) for elevation, in order to carry out hand thinning from November to January. The labour requirement for thinning ranges between 35-40 person-days/ha/yr.

6.2.2.6 Harvesting

Harvesting is undertaken once a year. Depending on the variety, pickers harvest a given block several times, in order to optimise fruit maturity, colour and size. In all the orchards, harvesting is undertaken, using manual labourers, who climb up aluminium ladders or hydra-lada to reach the fruit. The harvested fruit is put into bins, which are then brought to a central point, using a tractor and trailer and finally they are stacked into a truck with a forklift, for delivery to the pack-house. The time required for harvesting depends mainly on yield, variety and on the orchard's characteristics, such as size, age and distribution of trees. The labour input for harvesting ranges between 25-30 person-days per ha.

6.2.2.7 Irrigation

All the orchards studied are irrigated using the under-tree micro-sprinkler system. Water is pumped into the orchard from ground water, using an electric pump. Frequency of irrigation varies from orchard to orchard and depends on weather conditions, crop water use, soil water holding capacity and the quantity of water per irrigation. Irrigation is usually applied during the spring and summer months.

6.2.3 Miscellaneous information

Other information relating to the orchard includes the yield data, the transport of fruit to the pack-house, the machinery and equipment held on the orchards, the total human labour use and the frost protection system (when used).

Yield

Yield varies amongst the orchards depending upon the planting density, intensity of management practices, the variety of the fruit, plant population per ha and the weather conditions. The gross yield (fruit that is picked from the trees) ranges from 1900 to 3100 tce (tray carton equivalent) per ha, or 34 to 54 t/ha, respectively (tce is approximately 18 kg) (MAF, 2004). All the picked fruit is transported to the pack-house.

Transporting

Medium to large sized trucks (20 t tare weight) carry the fruit from the orchard to the pack-house. The pack-houses are located within 10-20 km from the orchards. Utes (utility vehicles) and tractors are commonly used in the larger orchards, to transport labourers and equipment (such as aluminium ladders, sprayers and any other tools), from one block to the other. Transportation of compost is an important input in organic apple orchards. Compost is transported from a distance of approximately 100 km.

Human labour use

Human labour is required to run the machinery, to carry out various operations, prepare sprays, prune, thin, harvest, perform paper work to obtain organic certification, repair and maintain equipment, manage the farm and undertake other miscellaneous operations. The total labour use across the orchards is estimated to be 95-110 person-days/ha/yr.

Machinery and equipment held at the orchards

The list of machinery and equipment held at the orchards is presented in Table 6.3. All the orchards use a tractor, sprayer, mulcher, mower, hydra-lada, utes, forklifts, aluminium ladders and a trailer.

Table 6.3 List of machinery/equipment held at organic apple orchards

Item	Number held
Tractor; 45-55 kW	1-3
Air-blast sprayer; 2000 L	1-3
Mulcher; 700-800 kg	1-2
Swing arm mower; 500-600 kg	1-2
Hydra-ladders; 10 hp petrol	3-5
Utes; 1200 kg	1-2
Forklifts; 40-45 kW	1-2
Aluminium ladders; 10 kg	15-45
Trailer; 500 kg	1-2
Fertiliser spreader; 250 kg	1-2

Note: Mass of the equipment is growers' estimate

Frost fighting

Frost fighting operations are aimed at avoiding damage at the sensitive stages of crop growth, when the temperature falls below 0^0C. Only two orchards use wind machines on their frost-susceptible blocks. The other orchards did not have any protection from frost, since those orchardists believe that frost is not an issue, because of the site specific advantages of their orchards.

6.3 Two different organic apple systems

From the information gathered from the growers, it is observed that there is a wide range in the use of management inputs, planting density and variety mix, across the orchards studied. These differences, plus other factors such as the rootstock, the timing of previous year's thinning and crop vigour, might be contributing to a variation in the total yield across the orchards, which ranged from 34 to 54 t/ha. Due to these inherent differences, it was decided to develop two separate model systems for sustainability analyses. The first system represents the orchards which are semi-intensive, with lower yields and to which a relatively lower number of sprays are applied, whilst the other system represents orchards which are intensive, with higher yields, and uses a higher number of sprays. These two systems are described and analysed for sustainability in the following sections.

6.3.1 The model semi-intensive organic apple system

The model semi-intensive organic apple system is a 10 ha property. The distance between the rows is 5 m and between the trees it is 2.5 m, thus giving a plant population of 800 trees/ha. The variety mix consists of 40% Royal Gala, 30% Braeburn, and the remaining 30% is composed of Pacific Beauty, Pacific Rose and Pacific Queen, all grafted onto MM-106 rootstock. The gross yield is 2050 tce per hectare. This value is equal to 36.9 t/ha. The entire system is irrigated from one bore, through an under-tree micro-sprinkler system. There is no frost fighting machinery installed. Trees are supported with two tiers of galvanised wires tied to two wooden posts at the end of each row and by further posts every five trees. The pack-house is located 10 km from the orchard. The total human labour use is estimated to be 110 person days/ha/yr, which includes the sum of human labour to run the machines, prune, harvest, thin, prepare sprays, repair and maintain the machinery and equipment, monitor pest incidence, undertake paper work to manage the orchard and also to carry out miscellaneous operations.

Machinery and equipment used in the semi-intensive system are presented in Table 6.4.

Table 6.4 Machinery/equipment held at the model semi-intensive organic apple system

Machinery/equipment	**Power or mass**	**No**
Grower owned		
Tractor	50 kW	1
Forklift	32 kW	1
Mower	600 kg	1
Mulcher	800 kg	1
Sprayer	500 kg	1
Hydra lada	10 hp	2
Aluminium ladders	10 kg	15
Spreader	250 kg	1
Contracted**		
Shelter-trimmer	80 kW	NA
Trucks	20000 kg	NA
Compost spreader	1400 kg	NA

NA Not applicable
Note: Mass of machinery and equipment represents tare (empty) weight and is based on growers' estimate
***Assumed to work on 200 ha per year with a working life of 15 years, except for the truck, which is assumed to work over 300 ha in one year.*

The spray programme for the semi-intensive apple system is described in Table 6.5. A spray volume of 2000 L/ha is used except for biostimulants, for which a spray volume of 1000 L/ha is used.

Table 6.5 Spraying programme of the model semi-intensive organic apple system

Material per 100L water	No of passes	Rate/ha/yr*
Fungicides		
Lime sulphur; 1L	5	100 L (127 kg)
Copper fungicides; 32g	7	5.2 kg
Sulphur fungicides; 100g	6	12 kg
Insecticides		
Codling moth granulosis virus; 5ml	6	600 ml (660 g)
Spinosad (macrocyclic lactone); 6g	4	480 g
Mineral oil; 1L	1	20 L
Biostimulants**		
Molasses	1	15 L
Compost tea	1	100 L
Seaweed spray	1	20 L
Liquid fertilisers		
Magnesium sulphate; 100g	1	1 kg
Total number of sprays	**29*****	

** Volume is converted into mass by multiplying with respective specific gravity*
***Total water used is 1000L/ha*
**** Compatible materials are mixed together and hence the total number of sprays is less than the sum of the number of passes*

The semi-intensive apple system's fertiliser programme is reported in Table 6.6. Agricultural lime is applied every year as a soil conditioner and Biophos is used at the rate of 500 kg. Biophos is an organic fertiliser prepared with the aid of microbiological technology, which contains nitrogen, phosphorus, potassium and marginal quantities of sulphur, magnesium, sodium and calcium in proportion, as presented in Appendix II.

Table 6.6 Fertiliser application programme of the model semi-intensive organic apple system

Material	Rate/ha/yr
Biophos	500 kg
Agricultural lime	300 kg

The fuel consumption in various operations and inputs for the semi-intensive system are presented in Table 6.7. The total diesel and petrol use is 441 L/ha/yr and the lubricant requirement is 18 L/ha/yr (growers estimated 4 L of lubricant use for every 100 L diesel).

Table 6.7 Fuel consumption of the model semi-intensive organic apple system

Operation	Work rate hr/ha	Fuel use L/pass*	No of passes/yr	Total fuel use L/ha/yr
Spraying	0.60	6.3	30	189
Mowing	0.75	7.8	6	47
Mulching	2.00	21.0	1	21
Fertiliser spreading	0.60	6.3	2	13
Hedge trimming	0.50	10.5	1	11
Harvest tractor	3.00	21.0	1	32
Harvest forklift	1.00	8.4	1	8
Harvest Hydra lada	16.00	32.0	1	32
Pruning Hydra lada	25.00	50.0	1	50
Thinning hydra-lada	17.00	34.0	1	34
Compost spreading**	4.00	4.0	1	4
Total				441

** Estimated as per equation 4.6*
***Fuel required for compost spreading is based on growers' estimate.*

6.3.2 The model intensive organic apple system

The model intensive system is a 65 ha property. The 65 ha property is divided into four separate blocks, located within a physical proximity of 5 km. Rows are spaced 4 m apart and the distance between trees is 2 m, thus giving a plant population of 1250 trees/ha. The variety mixture consists of 30% Royal Gala, 30% Braeburn, 25% Fuji, 10% Pacific series and the remaining 5% Granny Smith, Cox Orange Pippin and other cultivars. The gross yield of the intensive system is 3100 tce, which is 54 t/ha. The trees are grafted predominantly on MM-106 and M-793 is present, to a lesser extent. Trees are supported with two tiers of galvanised wires and tied to two wooden posts at the end of each row. Wooden posts support the galvanised wires after every 12 trees. The entire 65 ha property is irrigated by four bores. Aerial application of *Bacillus thuringiensis* is carried out three times a year using a helicopter. The pack-house is located 10 km from the orchard. The total human labour requirement for the intensive apple system is 95 person-days/ha/yr.

The machinery/equipment and the specifications of each item in the intensive system are presented in Table 6.8.

Table 6.8 Machinery/equipment held at the model intensive organic apple system

Machinery/equipment	Power or mass	No held
Grower owned		
Tractor	50 kW	3
Forklift	37 kW	2
Mower	600 kg	3
Mulcher	800 kg	2
Sprayer	500 kg	3
Hydra lada	10 hp	9
Aluminium ladders	10 kg	40
Fertiliser spreader	250 kg	2
Contracted*		
Shelter trimmer	80 kW	NA
Truck	20000 kg	NA
Compost spreader	1400 kg	NA
Bell Jet Ranger Helicopter	720 kg (empty)	NA

NA = not applicable
Note: Mass represents the tare (empty) weight of the machinery/equipment
**Assumed to work on 200 ha per year with a working life of 15 years, except for the truck and helicopter, which are assumed to work over 300 ha in one year.*

The spraying programme for the intensive apple system is described in Table 6.9.

Table 6.9 Spraying programme of the model intensive organic apple system

Material per 100L water	No of passes	Rate/ha*
Fungicides		
Lime sulphur; 1 L	16	320 L (406.4 kg)
Copper hydroxide; 32 g	10	7.4 kg
Elemental Sulphur; 100 g	2	4 kg
Insecticides		
Codling moth granulosis virus; 1ml	1	20 ml (22 g)
Spinosad (macrocyclic lactone); 6g	2	240 g
Mineral oil; 2 L	2	40 L
Biostimulants**		
Molases ; 1.5 L	1	15 L
Wuxal amino; 150 ml	1	1.5 L
Biomin calcium; 75 g	1	1.5 kg (1.18 L)
Aerial sprays		
Bacillus thuringiensis; 25 g	3	300 g
Total number of sprays	**38**	

** Volume is converted into mass by multiplying with appropriate specific gravity.*
*** Total water used is 1000L/ha. Compatible materials are mixed together and hence the total number of sprays is less than the sum of the number of passes.*

The fertiliser programme of the intensive apple orchard is presented in Table 6.10.

Table 6.10 Fertiliser application programme of the model intensive organic apple system

Material	Rate/ha/yr
Agricultural lime	500 kg
Blood and Bone	500 kg
Rock phosphate	100 kg
Kieserite	300 kg

The total fuel requirement for the intensive apple system is presented in Table 6.11. The lubricant requirement is 23 L/ha/yr (growers estimated 4 L of lubricant use for every 100 L diesel or petrol).

Table 6.11 Fuel consumption of the model intensive organic apple system

Operation	**Work rate hr/ha**	**Fuel use L/pass***	**No of passes/yr**	**Total fuel use L/ha/yr**
Spraying	0.75	7.87	35	275
Mowing	1.00	10.50	4	42
Mulching	2.50	26.25	1	26
Fertiliser spreading	0.75	7.87	3	24
Hedge trimming	0.50	10.50	1	11
Harvest tractor	4.00	42.00	1	42
Harvest forklift	1.00	9.71	1	10
Harvest Hydra-ladder	20.00	40.00	1	40
Pruning Hydra lada	27.00	54.00	1	54
Thinning hydra-ladder	20.00	40.00	1	40
Compost spreading**	0.50	4.00	1	4
Miscellaneous ute	-	5.00	-	5
Miscellaneous tractor	-	5.00	-	5
Helicopter jet fuel***	0.06	6.00	3	18
Total				**596**

Note: Ute and tractor are used for transport of men and equipment within the blocks.
**Fuel use in L/ha/pass is calculated as per equation 4.6.*
***Based on growers' estimate*
**** Aerial spraying is assumed to be undertaken with the help of a Bell Jet Ranger type helicopter, which is commonly used in the region, the empty weight of which is 720 kg. Aerial spraying is undertaken three times a year, to administer Bacillus thuringiensis spray against leaf roller. The time required to spray a block of 13 ha is 30 minutes. Aviation fuel (Jet fuel) kerosene-type is used in aerial spraying at the rate of 100 L/hr. The working area per year for the helicopter is 300 ha and the working life is 15 years.*

6.4 Sustainability analyses of the two model organic apple systems

The description of the model organic apple systems were described in the above section. This data is used in conjunction with the data from the published data and sustainability indicators were estimated using computer modelling tools, as described in the methodology. Sustainability assessments of the two organic apple systems are described, consecutively, below.

6.4.1 Sustainability indicators of the model semi-intensive organic apple system

The schematic representation of the model organic semi-intensive apple system and the equations in Stella® are presented in Appendix IV. Information on the fertiliser programme of the semi-intensive system forms an input into the Overseer® nutrient budget programme, in order to predict the nutrient balances and leaching of N. The sustainability indicators of the model organic semi-intensive apple system are presented below.

6.4.1.1 Energy ratio

The energy ratio of the model semi-intensive organic apple system is 1.57. This suggests that the system is efficient in converting input energy into fruit energy output.

The total energy input for the model semi-intensive apple system is 51.25 GJ/ha (Table 6.12). The yield of the semi-intensive apple system is 36.9 t/ha/yr. In energy terms, this comes to 80.44 GJ/ha/yr. Thus the semi-intensive organic apple system is able to produce more energy in fruit, than the amount of energy being consumed in fruit production. Spraying is the most energy intensive of all the management inputs (16.76 GJ/ha), followed by irrigation (10.06 GJ/ha) (Figure 6.2). Energy use in diesel is the highest energy input in the spraying operation (8.82 GJ/ha/yr), followed by embodied energy use in fungicides (4.47 GJ/ha/yr).

Energy in human labour, lime application, mulching, training, shelter-trimming, and lubricant use contributed to less than 5% of the total energy use respectively.

Table 6.12 Energy use and CO_2 emissions from individual operation/processes of the model semi-intensive organic apple system

Operation/processes	**Energy use MJ/ha/yr**	**CO_2 emissions kg/ha/yr**
Mowing	2,923	234
Mulching	1,508	121
Harvesting	5,687	455
Providing tree support	440	35
Lime use	180	129
Human labour use	2,013	NA
Lubricant use	812	32
Shelter-trimming	733	59
Irrigation use	10,069	604
Pruning/thinning	4,975	374
Fertiliser use	3,333	267
Spraying	16,767	1341
Transporting	1,818	145
CO_2 equiv. N_2O from Overseer®	NA	394
CO_2 from the soil	NA	14692
Total	**51,258**	**18,882**

NA not applicable

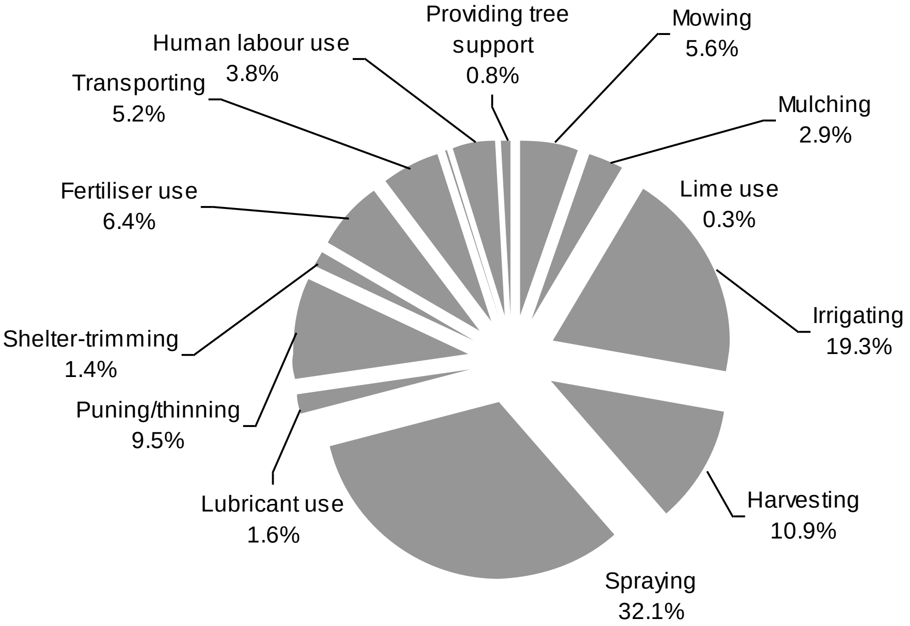

Figure 6.2 Energy use in the model semi-intensive organic apple system

6.4.1.2 CO_2 ratio

The CO_2 ratio of the model semi-intensive organic apple system is 1.24. The total CO_2-equivalent emissions from direct and embodied energy use and from the soil are 18.88 t CO_2/ha/yr. Soil is the major source of CO_2 emissions, which contributed 15.08 t CO_2/ha/yr. The total amount of CO_2 sequestered in apple trees is 23.57 t/ha/yr. The semi-intensive system model is therefore a net sink of CO_2, since it offsets the CO_2-equivalent emissions.

The release of CO_2-equivalent emissions from each activity is presented in Table 6.12. Soil is the major source of CO_2-equivalent emissions to the atmosphere, contributing to 80% of total emissions (15.08 t CO_2/ha/yr). The CO_2-equivalent emission from the use of direct and embodied energy is 3.79 t CO_2/ha/yr.

6.4.1.3 Changes in the soil carbon level

The model semi-intensive organic apple system sequesters 878 kg C/ha/yr in the soil from the addition of prunings, and roots. Each tree returns 22.37 kg CO_2/tree/yr in the form of prunings and roots. There are 800 trees per ha. Thus, 4,876 kg C/ha/yr is returned to the soil every year from the apple trees. From this amount, 3,998 kg C/ha/yr is lost in the form of CO_2 from the decomposition of soil organic matter and only 878 kg C/ha/yr can be expected to be sequestered to the orchard soil every year.

6.4.1.4 Nutrient balances

Overseer® estimates that of the primary nutrients, K is not supplied in adequate amounts (Table 6.13). This indicates that the K requirement of the crop has been met through depletion of the soil nutrient reserves. This suggests that K is being mined from the soil and therefore the nutrient management of the semi-intensive organic apple system is not considered sustainable. All other nutrients are supplied adequately for crop requirements.

Table 6.13 Nutrient balances of the model semi-intensive organic apple system kg/ha/yr (from Overseer®)

	N	P	K	S	Ca	Mg
Inputs	85	12	51	8	114	14
Outputs	29	3	87	1	7	3

6.4.1.5 Leaching of N

The nutrient balances suggest that N is supplied in surplus amounts, than what is exported in the output. Overseer® predicts leaching losses of about 22 kg N/ha/yr, whilst N-leaching losses to the drainage are up to 14 mg N/L. This level is considered a potential threat to the aquatic ecosystem, from eutrophication and also to human health.

The grass-legume understorey was a significant factor for causing N surplus and N-leaching losses, at levels that can be a potential threat of eutrophication. However, Overseer® predicted that the absence of grass-legume understorey caused no N-leaching losses at harmful levels: it failed to supply adequate amounts of N for crop requirements. This is because the legume was responsible for fixing atmospheric nitrogen, through biological nitrogen fixation.

6.4.2 Sustainability indicators of the model intensive organic apple system

The description of the model intensive organic apple system was described in section 6.3.2. The schematic representation of the model organic intensive apple system and the equations in Stella® are presented in Appendix V. Information on the fertiliser programme of the model intensive system formed an input into the Overseer® nutrient budget programme, in order to predict the nutrient balances and leaching of N.

6.4.2.1 Energy ratio

The energy ratio of the model intensive system is 1.84. An energy ratio of more than one suggests that the system is efficient in converting input energy to fruit energy output.

The total energy input for the model intensive apple system is 64.00 GJ/ha (Table 6.14). Spraying is the most energy intensive of all the operations/inputs (Figure 6.3), followed by irrigation. Energy in diesel use (12.86 GJ/ha) is the most energy intensive input in the spraying operation, followed by embodied energy in fungicides (10.73 GJ/ha).

The yield of the intensive apple system is 54 t/ha. In energy terms, this comes to 117.72 GJ/ha (as per equation 4.2). Thus, the model intensive system is able to convert more energy into fruit, than the amount of energy being consumed in its production process.

Energy in mulching, mowing, lime application, human labour and aerial spraying and shelter-trimming contributed to less than 5% of the total energy use, respectively (Figure 6.3).

Table 6.14 Energy use and CO_2 emissions from individual operation/processes of the model intensive organic apple system

Operation/processes	**Energy use MJ/ha/yr**	**CO_2 emissions kg/ha/yr**
Mowing	2,183	175
Mulching	1,389	111
Harvesting	5,106	408
Providing tree support	528	42
Lime use	300	215
Human labour use	1,710	NA
Lubricant use	1,171	47
Shelter-trimming	733	59
Irrigating	10,234	614
Pruning/thinning	4,919	345
Fertiliser use	3,972	287
Spraying	27,130	2,170
Aerial spraying	686	43
Utility vehicle use	805	64
Transporting	3,141	251
CO_2 equiv. N_2O from Overseer®	NA	122
CO_2 from the soil	NA	16398
Total	**64,007**	**21,351**

NA Not applicable

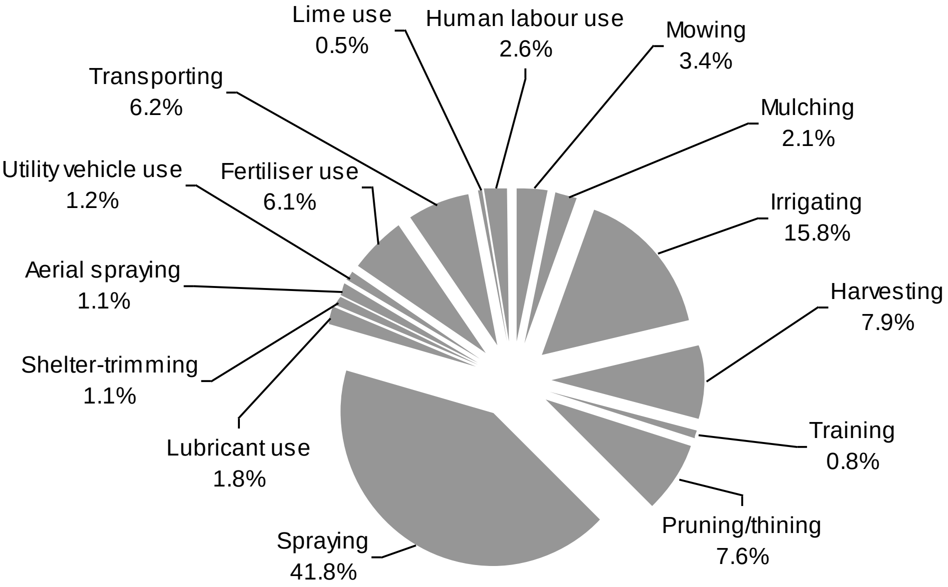

Figure 6.3 Energy use in the model intensive organic apple system.

6.4.2.2 CO_2 ratio

The CO_2 ratio of the model intensive organic apple system is 1.23. The CO_2 emissions of the intensive organic apple system is 21.35 t/ha. Soil is the major source of CO_2-equivalent emissions to the atmosphere, contributing to 77% of total emissions (16.52 t/ha) (Table 6.14). The CO_2-equivalent emissions from the use of direct and embodied energy is 4.83 t/ha (23% of the total emissions). The total amount of CO_2 sequestered in the apple trees is 26.31 t/ha/yr. Since the CO_2-equivalent emissions are offset, the system is a net sink of CO_2-equivalent emissions.

6.4.2.3 Changes in the soil carbon level

The model organic intensive apple system sequesters 980 kg C/ha/yr. From each tree in the model intensive system, 15.99 kg CO_2 is returned to the soil, in the form of prunings and roots. There are 1250 trees per ha. Thus, 5446 kg C/ha is returned to the soil every year from the trees. However, 82% of the carbon entering the soil is returned to the atmosphere as CO_2 in the same year, as described in the methodology. Thus, 4,466 kg C/ha is lost in the form of CO_2 whilst the remainder 980 kg carbon can be expected to be sequestered in the orchard soil every year.

6.4.2.4 Nutrient balances

Overseer® estimates that of the primary nutrients, K is not supplied in adequate amounts (Table 6.15). This indicates that the K requirement of the crop has been met through depleting the soil's nutrient reserves. As such, K is being mined from the soil and therefore the nutrient management of the model organic intensive system is a threat to future yield and sutainability. For all other nutrients, the inputs are higher than the outputs: this suggests that these nutrients are adequately supplied and meet the crop's requirements.

Table 6.15 Nutrient balances of the model intensive organic apple system kg/ha/yr (from Overseer®)

	N	P	K	S	Ca	Mg
Inputs	73	26	40	75	281	65
Outputs	44	7	132	70	69	15

6.4.2.5 Leaching of N

The nutrient balances suggest that N is supplied in surplus amounts, than that which is exported in the output. Overseer® predicts leaching losses of about 8 kg N/ha/yr. In terms of leaching, this value comes to 5 mg N/L. This level is considered as a potential threat to aquatic ecosystem from eutrophication, although it is considered safe for human health.

Similar to the kiwifruit and semi-intensive organic apple systems, the grass-legume understorey was a significant factor for causing N surplus and N-leaching losses, in the intensive organic apple system. Overseer® also predicted that the absence of grass-legume understorey caused no N-leaching, at levels that can be a potential threat of eutrophication. However, the absence of this understorey meant that N would not be supplied in adequate amounts.

6.5 Model responses to changes in key model inputs

As described in the methodology, management scenario analyses and sensitivity analyses are undertaken, in order to identify how well the model for sustainability assessment responds to changes in model inputs, in the two organic apple systems, respectively. These are described below.

6.5.1 Management scenario analyses of the organic apple systems

The typical orchard production practices of the two model organic apple systems were described in section 6.3. From the information gathered from the growers, it was noted that some of the key management practices were different from orchard to orchard, which might have an effect on sustainability. The effect of the key differences, in management practices on sustainability indicators in the semi-intensive and intensive organic apple systems, is described below.

6.5.1.1 Management scenario analysis of the semi-intensive organic apple system

The only key difference, within the management inputs in the semi-intensive organic apple systems, was the application of brought in (purchased from outside) compost. Compost was usually brought in and applied to the orchard at the rate of 8 t/ha, once every four years. Hence, compost application is not considered as a production practice within the model organic semi-intensive system. However, application of compost is considered by considering the 'what if' management scenario, as below.

What if the grower applies brought in compost?

Compost is applied once in every four years at the rate of 8 t/ha. Energy is required to prepare compost and transport it to the orchard. The energy in compost transportation is considered to be 3 MJ/t-km (Bone et al., 1996). Simultaneously, CO_2-equivalent emissions take place from the embodied energy used in the compost preparation and transportation. As a result, the energy ratio for the year when the compost is applied lowers from 1.57 to 1.38 and the CO_2 ratio lowers from 1.24 to 1.20. In this scenario, however, additional carbon is added to the soil from outside the orchard, in addition to carbon being added through prunings and roots. The total carbon added to the soil through prunings, roots and the addition of compost is 6,482 kg. Most of this carbon is returned to the atmosphere as carbon dioxide, through decomposition. It is estimated that about 5,315 kg is lost to the atmosphere as CO_2 and the remainder can be expected to be stored in the soil. As a result, 1,167 kg of carbon can be expected to be sequestered in the soil, compared to 897 kg of carbon when no brought in compost was applied. Also, as a result of additional N surplus through the application of brought in compost, the N-leaching losses went up from 14 to 17 mg N/L.

6.5.1.2 Management scenario analysis of the model intensive organic apple system

The description of the model intensive apple system, presented in section 6.3, represented the typical situation of intensive organic apple orchards. Compost is only applied in the model intensive organic apple system once in four years and therefore, compost application was not considered as a management practice, within the model intensive organic apple system. Similarly, a frost-fighting system is not included as an input in a typical model intensive organic apple system, because it is not used on all blocks. However, one of the blocks, in one particular orchard, was equipped with a wind machine to fight the frost. The wind machine is usually used for 70 hours in one season. Also, it is known, from the literature, that a smaller powered tractor consumes less amounts of diesel, compared to a high powered tractor, which carries out the same operations. A management scenario analysis was undertaken to identify the effect of these variations respectively on the model results. These management scenarios are presented below.

Scenario 1: What if the grower applies brought in compost?

Compost is purchased from commercial suppliers and applied once every four years at a rate of 8 t/ha. Energy is expended for compost preparation, in addition to transporting the compost to the orchard. The growers estimate that the compost is transported from 100 km away. With this scenario, the energy ratio is lowered from 1.84 to 1.66 and the CO_2 ratio from 1.23 to 1.20, compared to the base model which does not apply compost. When the compost is purchased, additional carbon is added to the orchard soil from outside the orchard. As a result, the total carbon added to the soil is increased from 981 kg/ha when the compost is not applied to 1269 kg/ha when the compost is applied. Also, due to the application of the compost, the N surplus increased which increased the N-leaching losses from 5 to 8 mg N/L.

Scenario 2: What if the grower uses a smaller tractor?

The literature suggests that diesel usage can be expected to be lower in denser plantings, because of smaller tree size that facilitate the passage of smaller equipment within the orchard, compared to semi-intensive apple system which requires larger tractors (Funt, 1980). However, no difference was found in the machinery/equipment used in the two model organic apple systems in this study. In fact, the diesel usage of the model intensive system was higher than the model semi-intensive system, due to frequent spraying and a higher work rate, necessitated by higher number of rows, than in the semi-intensive system.

The fact that similar sized machinery/equipment was used between the two model systems, in this study, can be explained by the number of trees and tree spacing. For example, the difference between the row spacing of the model semi-intensive and intensive orchard was only one metre (semi-intensive orchards had 5m between the rows, whilst intensive orchards had 4m between the rows). The semi-intensive orchard, in the study carried out by Funt (1980), had only 165 trees/ha and the intensive system had 1,512 trees/ha. In this study, the model semi-intensive system had 800 trees/ha and the intensive system had 1,250 trees/ha. There is not such a large difference in the number of trees/ha between semi-intensive and intensive apple orchards, compared to those studied by Funt (1980). The other reason, for the fact that the model intensive system had similar machinery/equipment size to those of the semi-intensive system, is the philosophy of the grower.

To see the effect of using a smaller tractor on the total energy use and CO_2 emissions, a hypothetical scenario was considered, in which the model intensive system used a 40 kW tractor instead of a 50 kW tractor: the time required to carry out the same operation was increased by 10% more than the based model. Under this scenario, the diesel consumption/hr is estimated as:

40 kW*0.35 L*0.6 = 8.4 L (as per equation 4.6)

Accordingly, the diesel requirement for individual operations is presented in Table 6.16.

Table 6.16 Fuel consumption in individual operations with a 40 kW tractor in the model intensive organic apple system

Operation	**Fuel used L/hr**	**Work rate hr/ha**	**Fuel use L/pass**	**No of passes**	**Fuel use (L/ha)**
Spraying*	8.4	0.86	7.22	35	253
Mowing	8.4	1.10	9.24	4	37
Mulching	8.4	2.75	23.1	1	23
Fertilisation	8.4	0.86	7.22	3	22
Harvest tractor	8.4	4.40	37.00	1	37
Total					**372**

** Number of sprayings excludes aerial sprays*

As a result of using a smaller tractor, the total fuel consumption of the model intensive organic apple systems, per ha per year, is reduced from 596 to 559 L/ha/yr. Also, the embodied energy invested in the tractor is lowered from 1,440 MJ to 1,170 MJ/ha/yr. As a result, the energy ratio elevated from 1.84 to 1.88 whilst the total energy input per ha reduced from 64.00 to 62.00 GJ/ha.

Scenario 3: What if the location of the orchard required the installation of the wind-machine?

A frost protection system was used by only one grower, on one of the blocks which was prone to the occurrence of frosts. On this block, a wind-machine, run for an average of 70 hours a year to minimise frost damage, was installed. The embodied energy in the frost fighting machinery was estimated to be 2,133 MJ/ha/yr, with a working life of 15 years (Appendix VI). It is assumed that, had the frost protection system not been installed in this particular block, then there would have been no marketable yield, since the majority of the fruit would have been frost damaged. Therefore, installing a frost protection system ensured that the yield from this block would be similar to those of the orchards, which do not have the problem of frost. In this scenario, the energy ratio lowered from 1.84 to 1.49 and the CO_2 ratio lowered from 1.23 to 1.16. This suggests that frost fighting consumes significant proportions of energy and contributes associated CO_2-emissions.

6.5.2 Sensitivity analyses of the organic apple systems

Sensitivity analysis was carried out for key model parameters, as described in the methodology. The results of sensitivity analyses, of the model organic semi-intensive and model organic intensive apple system, are presented in Table 6.17.

Both apple systems were insensitive to the uncertainties or known variation in all the key model parameters under investigation. These include the fruit energy content, fruit yield, embodied energy content in organic materials, CO_2 sequestered per individual apple tree, and CO_2 emission coefficient from the decomposition of organic matter.

The fruit energy content was assumed to be 2.18 MJ/kg apple following USDA (2007). Sensitivity analyses suggest that the model response will only change if the fruit energy content lowers from 2.18 to 1.4 MJ/kg in the semi-intensive system and 1.2 MJ/kg in the intensive system, respectively. This means that as long as the fruit energy content does not lower to these values, the model systems will be efficient in energy use, respectively.

The growers expressed the possibility of variation in yield, up to 5 t/ha/yr. According to the growers, variation in yield is mainly an issue in apple systems, due to the biennial cropping pattern of apple trees. Sensitivity analyses suggest that the model results change when the yield reduces by 12.5 t/ha/yr in the semi-intensive system and 24 t/ha/yr in the intensive system.

The embodied energy in organic materials was assumed to be 5 MJ/kg, in this research, following Helsel (1993). Sensitivity analyses suggest that the model results change only when the embodied energy content of the organic materials increases from 5 to 55 MJ/kg in the semi-intensive system and up to 135 MJ/kg in the intensive system.

Energy content in diesel is assumed to be 46.7 MJ/kg following Wells (2001). The model response changes only when the energy content in diesel increases from 46.7 to 139 MJ/L in the semi-intensive system and 167 MJ/kg in intensive system.

An average apple tree, in the semi-intensive system, is assumed to sequester 29 kg CO_2/yr, whilst an individual tree in the intensive system is assumed to sequester 21 kg CO_2/yr. Sensitivity analyses suggests that the system is carbon neutral, only when the sequestration in an individual tree lowers to 15 kg CO_2/yr and 11 kg CO_2/yr in the semi-intensive and intensive apple system, respectively. As long as the CO_2 sequestration does not reduce to these levels, the model results will not change.

Although all the carbon, which is added to the orchard soil through prunings and through roots, is released back from decomposition in the same year, the apple system remains a net sink of CO_2. This suggests that both the apple systems act as a sink of carbon, during woody perennial growth, throughout the growing season.

Table 6.17 Model responses to variation in parameters in both model organic apple systems

Model parameter	**Original value***	**New value to change the sustainability outcome****		**% variation from the original value**		**Uncertainty or known variation**	**Sensitive/ insensitive**
		Semi-intensive	intensive	Semi-intensive	intensive		
Fruit energy content MJ/kg	2.18	1.4	1.2	36	45	2.18-2.4 MJ/kg	insensitive
Yield*** t/ha/yr	a,b	24	30	35	44	5 t/ha/yr	insensitive
Embodied energy in organic materials MJ/kg	5	55	135	1,000	2,600	-	insensitive
Energy content in diesel MJ/L	46.7	139	167	197	257	±15%	insensitive
CO_2 sequestered per apple tree kg/yr	c,d	15	11	49	48	-	insensitive
CO_2 emission coefficient from soil organic matter decomposition %	82	100	100	22	22	-	insensitive

** The value is taken from published literature, as described in the methodology chapter*

*** Hypothetical value of the respective parameter to change the sustainability outcome from sustainability to unsustainability*

**** Growers estimated an average variation in yield of 5 t/ha/yr*

a Original yield value for semi-intensive system is 36.9 t/ha/y

b Original yield value for intensive system is 54 t/ha/yr

c CO_2 sequestration in an individual tree in a semi-intensive apple system is 29 kg/yr

d CO_2 sequestration in an individual tree in an intensive apple system is 21 kg/yr

- Uncertainty unknown

6.6 Summary

In this chapter, the sustainability assessment approach was applied to organic apple systems in New Zealand. In order to implement this approach, the organic apple orchards were first modelled, in terms of the information gathered from the growers. Two distinct apple systems were identified: the semi-intensive and intensive systems, respectively. A sustainability analysis was carried out for each system.

Both organic apple systems were efficient converters of energy input to energy output and they demonstrated a net sink of CO_2-equivalent emissions in the woody perennial growth and the soil. Both the systems mined potassium from the orchard soil, which is not sustainable and they leached nitrogen at levels that are potentially considered to cause eutrophication. The grass-legume understory was a significant factor that contributed to N-leaching, in both systems. Energy was saved through the use of a smaller tractor in the intensive system. A frost protection system consumed a great deal of energy and lowered the energy ratio and the CO_2 ratio, in the intensive system. Noticeably, higher amounts of carbon were sequestered in the soil, when the compost was purchased from outside, as compared to when no compost was applied. Both the model systems were insensitive to the uncertainties associated with key model parameters.

Chapter 7

DISCUSSION AND CONCLUSIONS

7.1 Introduction

The sustainability of agricultural systems is becoming more important all the time, yet there is no agreed upon best way to assess agricultural sustainability. Sustainability assessment in general continues to evolve. The key contribution of this research has been the development of a new sustainability assessment approach at the orchard systems level.

This research was carried out in two parts. First, the assessment approach was developed by addressing the following two research questions:

1. What constitutes sustainability at the orchard systems level?
2. How can sustainability be assessed at the orchard systems level?

Second, the application of the proposed assessment approach to organic kiwifruit and organic apple systems led to important insights into the sustainability of these systems and addressed the following research questions:

3. How well does the proposed approach work for assessing sustainability?
4. What are the key factors that influence sustainability of organic kiwifruit and organic apple systems in New Zealand?

The purposes in this chapter are to discuss the findings from this research in order to determine whether the proposed sustainability assessment approach is appropriate for assessing sustainability, to contribute to a greater understanding of the sustainability of organic kiwifruit and organic apple systems in New Zealand, and to draw conclusions and make recommendations.

7.2 The sustainability assessment approach

Sustainability is among the most pressing and urgent challenges facing agriculture today. The need for research and education to meet this challenge has been identified in virtually every recent study on agricultural research needs. The first task in developing an approach to sustainability assessment is to define what constitutes sustainability. In this research, sustainability of the orchard systems level is defined based on the theory of strong sustainability, which is rooted in thermodynamics and which also implies adherence to precautionary principle. Sustainability is defined by two criteria: an energy criterion – orchard systems should be efficient in terms of energy use; and an impact criterion – non-degradation of the environment from energy and material use.

Once the sustainability criteria were defined in the context of an orchard system, the next question was how to go about assessing sustainability. In order to do this, specific tools were needed for practically assessing sustainability at the orchard systems level. In order to assess the sustainability of an orchard system in a quantitative manner, indicators which are consistent with the criteria for sustainability were required. This resulted in the identification of five indicators: the energy ratio, the CO_2 ratio, changes in the soil carbon level, nutrient balances, and the leaching of nitrogen. The orchard production system's boundary for sustainability assessment includes the natural environment with which the orchard production practices interact. The embodied energy use and associated CO_2 emissions which take place outside the orchard are considered in sustainability assessment. Similarly, the N-leaching from the orchards, which affects the wider environment downstream, is considered in sustainability assessment. In this way, a systems approach based on life cycle thinking was used to understand the relationships among various components within an orchard production system.

The analytical approach for sustainability assessment at the orchard systems level is described in section 3.5. The application of the analytical approach to organic orchard systems in New Zealand is described in the methodology in Chapter 4. The effects of orchard management practices are related to energy efficiency and the environmental impacts arising from energy and material use. In this way, the whole orchard system was modelled by integrating two subsystems (energy use and environmental impacts) to improve the understanding of sustainability at the orchard systems level. Practically, sustainability assessment was carried out by using computer modelling tools that bring together component energy and material flows of the orchard system and relate them in a quantitative manner to estimate sustainability indicators. Linking Stella® and Overseer® enabled the estimation of the five sustainability indicators, which would have been not possible by using either tool in isolation. Using scenario analyses, it was possible to model the effect of changes in management practices on the energy efficiency and the environmental impacts. This enabled the identification of areas of improvement for moving towards more sustainable orchard management practices.

7.2.1 Sustainability assessment of the orchard systems

The application of the proposed approach to the organic orchard systems led to useful insights on sustainability assessment in general. Sustainability in this research is defined by two criteria. The first criterion for sustainability – the energy criterion is based on the first law of thermodynamics (Sollner, 1997; Jollands, 2006). The energy efficiency criterion for sustainability was quantified as the energy ratio. The energy ratio provided insights into how efficient the orchard system is in terms of conversion of energy input into food energy output (Pimentel et al., 1983). The total energy input of the orchard system was estimated as the sum of the energy used in individual key operations and processes in orchard production. In this way, the estimation of energy inputs enabled the identification of the highest energy-consuming operations at the orchard systems level (Reganold et al., 2001; Canals, 2003; ARGOS, 2005).

Although the energy ratio provides insights into the efficiency of energy conversion at the orchard systems level, it has to be interpreted with caution. There are two reasons for this. First, the energy ratio only indicates the output of useful food energy per MJ of energy invested. In reality, the various energy inputs used in orchard production processes are less than perfectly substitutable with each other or with the food energy in fruit (a MJ of fossil fuel is qualitatively different from a MJ of fruit energy) (Cutler, 2007). Second, dependence on non-renewable energy is, by definition, unsustainable; obviously, as long as any system depends on non-renewable resources, it will not be sustainable (Schroll, 1994; Edwards-Jones & Howells, 2001). Therefore, it seems logical that using less of these resources will almost always be more sustainable than using more of them. A reduction in the flow of non-renewable resources can be interpreted as progress towards sustainability (Haberl et al., 2004).

The second criterion for sustainability, the impact criterion – non-degradation of the environment from energy and material use, is based on the second law of thermodynamics (Steinborn & Svirezhev, 2000; Svirezhev, 2000). Degradation of the environment basically occurs in the atmosphere, soil, water and biodiversity (OECD, 2001). Degradation in the environment was addressed by quantifying four indicators – the CO_2 ratio, changes in the soil carbon level, nutrient balances, and N-leaching. The CO_2 ratio gives an indication of the global warming impact that occurs from the orchard production practices. In the CO_2 ratio, the role of orchard systems as a source as well as a sink for CO_2 is considered for estimating the net burden of greenhouse gases from orchard systems. This net balance approach provides a good reflection of an orchard system's net contribution to climate change (OECD, 1999).

The impacts of orchard production practices on the soil were indicated through changes in the soil carbon level and nutrient balances. Carbon is an important indicator of soil organic matter which in turn, is an indicator of soil quality (OECD, 2001). The inherent productivity of the soil is degraded when soil organic matter is declining (USDA, 2003). Hence, to be sustainable the orchard production system must exhibit signs that the inherent productivity is maintained or enhanced by addition of soil organic matter. At the orchard systems level, changes in the soil carbon level were estimated as the balance between carbon inputs and carbon losses, which indicated the amount of net soil carbon sequestration (Johnston, 1986; Paustian et al., 2000). Mining of primary and secondary nutrients from the soil is another indicator of declining soil fertility and soil quality (FAO, 2005). A change in soil fertility was estimated as the balance between nutrient inputs and outputs. Impacts on water quality at the orchard systems level were indicated by levels of N-leaching. Nitrogen levels in water above a certain limit are harmful to human health as well as to aquatic ecosystems (Di & Cameron, 2002; Pierzynski et al., 2005).

Although the sustainability assessment approach considers major impacts that occur in the atmosphere, soil, water and biodiversity over one growing season, limitations in the quantitative approach taken meant that some issues were not considered. For example, the use of copper in organic orchard systems is an issue that is important in the discussion of impacts on biodiversity (Morgan & Bowden, 1993; Merrington et al., 2002). Although none of the growers exceeded the BioGro limit of annual copper application of 3 kg/ha/yr (BioGro, 2004), it can be expected that year-after-year sprays of copper might lead to copper build-up in soil which can affect soil biodiversity adversely (Morgan & Taylor, 2003/2004). Also, organic orchard production negatively affects biodiversity in general through clearing of the land for orchard establishment (Gudmundsson & Hojer, 1996; OECD, 2004). On the other hand, organic orchard production practices may have beneficial effects on above-ground biodiversity. In general organic systems result in greater abundance of flora, birdlife and mammals than their conventional counterparts (Hole et al., 2005). Areas in organic orchards, such as the shelter-belts, harbour more biodiversity than the rest of the cropped area (Moller et al., 2007). However, these relationships could not be captured in the present framework. As more quantitative data become available, it may be possible to quantify the effects of management practices on biodiversity within this sustainability assessment framework.

Sustainability based on the theory of strong sustainability gives primary importance to environmental sustainability, followed by socio-economic concerns (Daly, 1991). This research suggests that organic orchard systems are sustainable environmentally in many respects. However, many argue that organic systems may be less sustainable economically since their yields are often lower than yields in the conventional systems (Stokstad, 2002). They suggest that the definition of sustainability should consider the three components of sustainability: economic, social, and environmental, simultaneously (Smyth & Dumanski, 1993; Gomez et al., 1996; Rasul & Thapa, 2004). Often it has been acknowledged that economic growth usually takes place at the cost of environmental degradation, suggesting a trade-off among the three components of sustainability (Douglass, 1984; Blaschke et al., 1991; Yunlong & Smit, 1994; Daly, 1994a).

Although socio-economic concerns are important, sustainability essentially has an environmental bottom line (Goodland, 1995; Goodland & Daly, 1996). This means, once the criteria for strong sustainability are met at the orchard systems level, other indicators of socio-economic criteria should be considered in sustainability assessment (Daly, 1991). Therefore, indicators that are consistent with socio-economic criteria for sustainability can be considered within the present framework for sustainability assessment, once the two environmental criteria are met.

7.2.2 How well does the proposed approach work for assessing sustainability?

The application of the assessment approach to the organic kiwifruit, organic semi-intensive apple and organic intensive apple production systems in New Zealand helped answer the third question posed in this research: how well does the proposed approach work for assessing sustainability? Addressing this question entails making a subjective decision on whether the approach used is reasonable for its intended application (Robinson, 2006).

Whether the proposed approach works for sustainability assessment was identified in two ways as described in the methodology (section 4.4.2). First, results from the sustainability assessment of organic kiwifruit and organic apple production systems were compared with the results from other similar studies; second, how well the model responds to changes in model inputs is identified (Sargent, 1998). The management practices of the growers and the model parameters taken from the literature constitute the model inputs. Determining how well the model responds to changes in these inputs was investigated through management scenario analysis and sensitivity analysis.

7.2.2.1 Comparing the results with previously published studies

Results from the sustainability assessment of the three orchard systems compared favourably to results from other similar published studies, suggesting that the assessment approach is able to give reliable results (Sargent, 1998). These comparisons are discussed below.

All the studied organic orchard systems in this research had energy ratios of greater than one and were efficient in the conversion of energy input to fruit energy output. These findings are consistent with the literature in which orchard systems were energy efficient in the conversion of energy input into fruit energy output (Strapatsa et al., 2006; Esengun et al., 2007). For example, organic apple systems in the USA had an energy ratio greater than one, suggesting that those systems were sustainable from an energy efficiency point of view (Funt, 1980; Reganold et al., 2001).

The energy required to produce one tonne of organic apple fruit in this research was estimated as 1389 MJ and 1185 MJ in the semi-intensive and intensive systems, respectively. These values are comparable with Canals (2003), who reported energy use of 1250 MJ to produce one tonne of organic apples in the Hawke’s Bay region of New Zealand, and are slightly higher than the energy use reported by Saunders et al. (2006) for conventional apples in New Zealand (950 MJ per tonne). The higher energy use in organic apple systems relative to conventional systems is thought to reflect a more intensive spray program (Percy, 1996; MAF, 2004). The higher number of sprays in organic apple systems is attributed to the susceptibility of apple varieties to black spot and powdery mildew, which are difficult to control under organic regimes (McCarthy, 1994). In order to control these diseases, lime sulphur and copper sprays are used, which have high embodied energy content. This is probably the reason why spraying used the most energy of all the operations in all the model systems studied in this research. These results are consistent with the previously reported studies by Strapatsa et al. (2006) in which most of the energy use in an integrated apple system was in disease and pest control.

The total energy used by the organic kiwifruit system in this research was 34.15 GJ/ha/yr, while the direct energy consumption (energy in diesel, lubricants and human labour) was 10.5 GJ/ha/yr. These values are comparable with the median energy input of 35 GJ/ha/yr (total energy) and 14 GJ/ha/yr (direct energy) in twelve organic kiwifruit orchards studied in New Zealand previously (ARGOS, 2005).

All three organic systems had CO_2 ratios of more than one, and sequestered carbon in the soil through the addition of organic matter. These findings are consistent with the idea that orchard crops have the potential to store carbon in woody perennial growth as well as in the soil, and can be a net carbon sink (Horticulture New Zealand, 2007; Kerckhoffs & Reid, 2007; OANZ, 2008).

In both apple systems, output of potassium in fruits was higher than the input. This suggested that potassium supplied from the inputs would not meet the crop’s need, and therefore, the potassium requirement of the crop is met through depleting soil reserves. These findings are consistent with previous studies in which soil potassium deficiencies in organic apple orchards have been reported (Haynes, 1998; Kessel et al., 2007). Depletion of soil potassium reserves is considered a threat to future yield and sustainability. Therefore, it has been suggested that the organic orchardists must consider how to use the permitted fertiliser options under organic certification to replace potassium losses from the soil (Condron et al., 2000).

All three organic orchard systems leached nitrogen at levels that could be considered as a potential threat to aquatic ecosystems following the threshold level considered in this research (Pierzynski et al., 2005). The N-leaching losses between 5-14 mg N/L were predicted from the organic apple systems in this research. These levels are low when compared to the N-leaching losses of 20-26 mg N/L from a conventional apple orchard in the USA (Merwin et al., 1996); the N losses from conventional orchards in New Zealand are not known. Similarly, relatively low leaching losses of 11 kg N/ha/yr were estimated from the organic kiwifruit system in this research, while leaching losses of 50 kg N/ha/yr have been reported from a conventional kiwifruit orchard in New Zealand (Ledgard et al., 1992). Although no direct comparison with organic orchard systems was made, the findings suggested that organic systems might leach lower levels of N than conventional systems (Hansen et al., 2000; Knudsen et al., 2006).

7.2.2.2 Model responses to changes in management practices

Management practices are an important input to the model. A good model should be able to demonstrate changes in model response when changes in management practices occur (Sands & Podmore, 2000). Management scenario analysis (Chapters 5 and 6) suggested that the model responds to variations in key management practices, and therefore, helps to identify areas to target for improving sustainability. The key areas in management where improvement in sustainability can be achieved in terms of saving energy and increasing soil carbon sequestration are described below.

Scenario analysis in the organic intensive apple system (Chapter 6) suggested that savings in energy and an associated increase in the energy ratio can be achieved with the use of smaller-sized (lower powered) tractor. This is consistent with other studies where diesel usage per hour was reduced with smaller machinery in organic apple orchards in the USA (Funt, 1980).

In the organic kiwifruit system, savings in energy and an increase in energy ratio occur when the compost is prepared on the orchard instead of being purchased from outside. This is logical because of the saving in the energy in transporting the compost, which uses a lot of energy (Barber & Scarrow, 2001). However, there is a trade-off associated with this management decision; the energy ratio improves, but the amount of carbon sequestered in the orchard soil decreases when the compost is prepared on the orchard. This is logical because compost made on orchard only recycles organic matter, whereas compost brought in adds organic matter, which leads to higher level of carbon sequestration. Similar findings occurred in both apple systems in which the energy ratio decreased but carbon sequestration increased when compost was brought in as compared to when compost was not applied. The reasoning is consistent with the fact that amount of carbon input to the soil is one of the important factors influencing carbon sequestration in the system

(Paustian et al., 2000). This suggests that managing organic orchard systems for environmental sustainability is a challenge because trade-offs might be involved within different components of the environment.

7.2.2.3 Model responses to changes in model parameters

Sensitivity analysis was undertaken to identify the model's response to the uncertainty associated with key model parameters. The sensitivity analysis suggested that the results from the sustainability analyses were insensitive to uncertainties associated with the following model parameters: fruit energy content, fruit yield, embodied energy of organic materials, energy content in diesel, and CO_2 sequestration by individual plants. Insensitivity of the model results to the uncertainties associated with key model parameters suggests that the known variation in the model inputs does not affect the conclusion regarding sustainability.

The fruit energy content used in this research was based on the USDA food nutrient database for kiwifruits and apples (USDA, 2007). The literature suggests that the fruit energy content does not vary significantly within the same species. For example, the fruit energy content of fresh apples can range from 2.18 MJ/kg to 2.4 MJ/kg (Strapatsa et al., 2006; USDA, 2007). It is not known whether the energy content reported by Strapatsa (2006) is the gross energy or the physiologically available energy. In this research, the physiologically available fruit energy content in the apple and the kiwifruit systems was assumed to be 2.18 MJ/kg and 2.5 MJ/kg respectively, based on USDA (2007) values. Sensitivity analysis suggests that energy use in organic orchard systems would be inefficient only if the fruit energy content is reduced to 1.7 MJ/kg in kiwifruit system, 1.4 MJ/kg in semi-intensive and 1.2 MJ/kg in intensive apples. However, it is unlikely that the energy content in fruit can lower to these levels. As long as the energy content of the fruit remains above these levels, the model results will not change.

The second parameter analysed for sensitivity was the fruit yield per ha per year. The fruit yield was converted into fruit output energy by multiplying it with the appropriate fruit energy content. Growers suggested that the maximum variation in yield was ±5 t/ha/yr in the organic kiwifruit and in both organic apple systems. Sensitivity analysis suggests that the model systems would become inefficient in terms of energy use only if the yield is reduced from 21 to 13.5 t/ha/yr in kiwifruit system, from 36.9 to 30 t/ha/yr in semi-intensive apple system, and from 54 to 24 t/ha/yr in intensive apple system. This means that the model result will not change if the yield varies by ±5t/ha/yr in the studied orchard systems.

The embodied energy content for organic material inputs such as compost tea, fish meal, blood and bone, biostimulants and molasses was adapted from the study of Helsel (1993) to be 5 MJ/kg. It is generally acknowledged that organic materials have a lower embodied energy content because they are usually derived from natural products and require lesser amounts of energy in formulation than inorganic inputs used in the orchard (Florida Energy Extension Service & Helikson, 1991). Sensitivity analysis suggests that the model result is sensitive to the variation in the embodied energy content of organic materials only when the value for this parameter increases to 60, 55, and 135 MJ/kg (an increase of over 1000% over the original value of 5 MJ/kg) in the organic kiwifruit, organic semi-intensive, and organic intensive system, respectively. Since such increases are unlikely, the results from sustainability assessment will not change in response to these variations in embodied energy content.

The value for the CO_2 sequestration rate for individual kiwifruit vines and apple trees per year was taken from the published literature (Lakso & Johnson, 1990; Greer et al., 2004). This value was assumed to be 27 kg CO_2/yr for a kiwifruit vine, 29 kg CO_2/yr for an apple tree in a semi-intensive orchard and 21 kg CO_2/yr for an apple tree in an intensive orchard. Sensitivity analysis for kiwifruit and apple systems indicated that the CO_2 ratio is reduced to below one (the system becomes net source of CO_2 emissions) when the CO_2 sequestered per individual plant decreases to 15 kg/yr for a kiwifruit vine, 15 kg/yr for an apple tree in a semi-intensive system, and 11 kg/yr for an apple tree in an intensive system, respectively. Logically, it is unlikely that an individual kiwifruit vine or an apple tree in full crop, such as the ones in this study, will have a CO_2 sequestration rate reduced to this extent (close to a reduction by 50%) under average conditions of weather and management practices.

Diesel is the most common type of fuel used on the orchard for carrying out the orchard production practices. The energy content in diesel used in this research was 46.7 MJ/L (Wells, 2001). There is an uncertainty of ±15% associated with diesel energy content (Biodiesel board, 2007). Sensitivity analysis suggests that the model results change only when this parameter value increases by over 190% in all the studied systems. This means that a change of ±15% in this parameter value will not have any effect on the model results.

The sensitivity analyses undertaken in this research suggests that the model results for sustainability in general are insensitive to large variations in most of the key model parameters. The insensitivity of the model results to a large variation in model parameters does not necessarily mean that the model is unsuitable for the intended use. Models have been insensitive to large variations in model parameters in the past, and they were still considered effective and useful for their intended application (Sands, 1986; Martin et al., 2006). For example, the ESI (Environmental Sustainability Index) varied by only 2.7% in response to a variation of 40% in the field slope, as recorded by Sands and Podmore (2000). In another study, a 50% variation in soil erosion caused the emergy ratio to change by less than 10%, and so the emergy ratio was considered insensitive to the variation in soil erosion (Martin et al., 2006). A decision on how sensitive a model is to the variation in model parameters and whether that is desirable or not, depends on the specific context in which the model is built and on its intended use.

One possible reason why the results for sustainability did not change in response to the large variations in some model parameters might be the threshold values considered in this research. It might be expected that in situations where the threshold values for sustainability become more stringent, a lower variation in model parameters might be sufficient to change the model result. For example, the sustainability threshold for the energy ratio and the CO_2 ratio was considered to be one in this research. This means that the systems should at least break-even in terms of energy use and should not be a source of CO_2 to the atmosphere. In reality, there is no natural law that suggests which energy output to energy input ratio is the best; the decisions for an appropriate energy ratio, and which parameters should be included in the energy analysis, are primarily social and economic rather than environmental (Ruth, 1993; Scheraga, 1994; Schroll, 1994; Robert, 1997; Haberl et al., 2004). An energy ratio of 2 has been suggested as a target for sustainability to be achieved over a period of ten years for Danish agriculture (Schroll, 1994). If such a high target threshold was identified as appropriate for New Zealand orchard production systems, then this will have a bearing on the interpretations of the results from the sensitivity analysis.

The only parameter to which the model organic kiwifruit system was sensitive was the soil CO_2 emission coefficient from the decomposition of organic matter. In the model, this coefficient was assumed to be 82% relative to soil carbon input, following Grogan and Matthews (2002). Grogan and Matthews (2002) derived the CO_2 emission coefficient using a simple mass balance of soil carbon inputs and outputs on an annual time scale in a coppice willow bioenergy system. In their study, the decomposition rate constants for each of the soil carbon pools were derived from a long-term record of changes in soil carbon. An increase in this coefficient value from 82% to 95% would be sufficient to lower the CO_2 ratio below the sustainability threshold in the organic kiwifruit system. This means that if 95% of the carbon that enters the soil through organic matter returns back to the atmosphere through decomposition, then the kiwifruit system is not a net sink of CO_2. The reason why only the kiwifruit model was sensitive to the variation in the CO_2 emission coefficient might be because of the assumption that kiwifruit required more pruning (50% of wood is pruned in kiwifruit compared to only 30% in apples), which returned more organic matter to the soil, and subsequently produced higher emissions of CO_2 in proportion to sequestration. However, these findings could not be compared with other studies due to the lack of available data.

7.2.3 Sustainability of organic kiwifruit and organic apple systems in New Zealand

The application of the assessment approach to the organic kiwifruit and organic apple systems helped answer the fourth research question, namely, what are the factors that influence the sustainability of these orchard systems in New Zealand? As discussed below, the assessment of these systems provides important insights into the development of policy, identifies areas in orchard management which could be improved to move towards more sustainable practices, and suggests future areas of research that might increase the sustainability of these systems.

7.2.3.1 Guidance in the development of policy

To be effective, a good sustainability assessment approach should have policy relevance (United Nations, 1992). Assessment of the organic orchard systems led to the identification of two areas which have policy relevance for New Zealand conditions. These are the CO_2 emissions with regard to the Kyoto Protocol, and N-leaching and water quality.

CO_2 emissions and the Kyoto Protocol

The net carbon sequestered in the plant biomass and in the soil is estimated in this research to be 5.4 t/ha/yr, 7.7 t/ha/yr and 8.3 t/ha/yr for the organic kiwifruit system, the semi-intensive apple system, and the intensive apple system, respectively. These findings are relevant to New Zealand's Kyoto Protocol obligations. According to the Kyoto Protocol, each country must be able to offset its CO_2 release by adopting processes such as sequestration through tree-planting, changing farming methods, or using less of fossil fuels (Save the Planet, 2005). If a country produces more CO_2 than it can absorb, it must purchase 'absorption ability' from other nations through carbon credits. The carbon credit is a new currency and one carbon credit is equal to one tonne of CO_2 and is called a CO_2e (CO_2-equivalent) (NZ Government, 2007). New Zealand ratified the Kyoto Protocol in 2002 and is committed to reducing the CO_2-equivalent emissions in its effort to achieve sustainable development.

Recently, the New Zealand Government passed the bill for the Emissions Trading Scheme (ETS) as its core price-based measure for reducing greenhouse gas emissions in meeting its Kyoto Protocol obligations (Ministry for the Environment, 2008). The agriculture sector will be included under the New Zealand Government's Emissions Trading Scheme from 2013. The application of the ETS at the orchard systems level means that the organic growers will need to pay for the CO_2 they release from liquid fuel they use on the orchards (MAF, 2002). This research suggests that all of the CO_2 that is emitted from the use of fossil fuels is offset by capture into the fruit crops and in the soil, and therefore the organic orchard systems in theory could be eligible to trade carbon credits.

N-leaching and water quality

The maximum nitrate nitrogen level in water proposed by the WHO and which is considered safe for human health (11.3 mg nitrate N/L) is the most commonly followed threshold value for N-leaching in water bodies in New Zealand (Di & Cameron, 2002; AgResearch, 2006). However, other studies suggest that negative impacts on biodiversity can occur at much lower levels (as low as 0.5 mg N/L) than those recommended by the WHO (Di & Cameron, 2002; Pierzynski et al., 2005). Assuming 0.5 mg N/L as the threshold, all the studied organic orchard systems in this research leached N at levels that are a potential threat to aquatic ecosystems. Surface runoff or groundwater discharge from orchard systems is one of the contributing factors for enrichment of N in lakes, ponds, bays and estuaries. In general, water entering lakes, bays, and estuaries come from the surrounding area, which is known as its catchment or drainage basin. Several natural and human factors influence the quality and quantity of water that ultimately reach surface water bodies (Pierzynski et al., 2005). Although the studied systems could be considered as potential threats of eutrophication according to the threshold level as suggested by Pierzynski (2005), the N-leaching levels from the studied systems could not be compared with N levels that can cause eutrophication under New Zealand conditions. This is because there is no defined threshold value for N-leaching that is considered to potentially cause eutrophication in New Zealand aquatic ecosystems. Hence, such a threshold value for New Zealand conditions has to be identified as a basis for future policy-making.

7.2.3.2 Improvement in management to move towards more sustainable practices

The proposed assessment approach is useful for monitoring energy efficiency and environmental impacts of the studied orchard systems. As each of the indicators is assessed, the relative importance of the various components making up each indicator is identified. In this way, the assessment approach helps to identify specific management practices that either contribute to or detract from the move towards achieving sustainability.

It can be anticipated that increasing public awareness about the energy use and the carbon footprint[24] of goods and services will accelerate changes in orchard production practices, especially as New Zealand growers seek to differentiate their products in international markets. This means there will be increased pressure at the orchard production level to find efficient production practices with the overall aim to achieve sustainability. The sustainability assessment of the organic orchard systems identified three areas of improvement in management practices at the orchard systems level. These areas are: (1) strategies to mitigate nutrient mining and improve soil quality; (2) strategies to mitigate N-leaching and improve water quality; and (3) strategies to save energy and improve the carbon footprint.

Strategies to mitigate nutrient mining and improve soil quality

This research identified that nutrient management on orchards is an area of concern. The sustainability assessment indicated that both apple systems relied on soil potassium reserves to satisfy their potassium requirements. Organic orchard systems are usually faced with the challenge of supplying adequate amounts of nutrients to satisfy the crop requirements within the range of fertilisers permitted under organic certification schemes (Canals, 2003). In studied organic apple systems, compost was applied once in four years, and biophos (a certified organic fertiliser) was applied annually, both of which supplied some potassium. However, the total potassium supplied from these fertilisers was not adequate for crop needs. As a result, this nutrient is mined from the soil nutrient pool, which must be

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[24] Carbon footprint is the measure of the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in terms of carbon dioxide.

replaced with permitted potassium-containing fertilisers under the official organic certification scheme and with annual applications of certified compost. Potassium sulphate is a major source of potassium (about 40% potassium) which is a restricted compound[25] under official organic certification standard (BioGro, 2004). Patent kali is another fertiliser approved under official organic certification standard, which contains about 30% potassium. Certified compost is another source of potassium, although to a much lesser extent (about 0.5%-1.0% potassium). The growers apply compost only once in four years in both the apple systems. Hence, annual application of composts, application of potassium sulphate, and increased use of biophos may alleviate potassium deficiencies in the orchard soil. However these may have effect on leaching losses and total energy use.

Strategies to mitigate N-leaching and improve water quality

All the studied systems leached nitrogen at levels which could be a potential threat to aquatic ecosystems downstream. Nitrogen inputs to the orchard systems are from compost, rainfall, irrigation if used, and from the maintenance of permanent grass-legume understorey. Overseer® predicted that the grass-legume understorey was a significant factor that influenced N-leaching losses at levels that can be a potential threat of eutrophication. At the same time, Overseer® predicted that maintaining the orchard understorey without grass-legume vegetation leads to a potential deficiency of nitrogen, which can affect yield adversely. This suggests that there is an issue of balancing the nutrient management to supply adequate N, while minimising N-leaching losses. Maintaining lower proportions of clover density in the understorey might help to mitigate N-leaching in the organic orchard systems. Also, the choice of other legume species, which provides the proper amount of N-release for the crop's requirement, might reduce N-leaching losses.

Strategies to save energy and improve the carbon footprint

The growers usually prefer to use bigger tractors. Using bigger tractors means greater embodied energy content and higher fuel consumption. This research suggested that the diesel usage per ha can be lowered by using a low-powered

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[25] Written permission must be obtained from BioGro prior to using the compound. Each year there must be reduction in dependence on these restricted fertilisers (BioGro, 2004).

smaller tractor (from 50 kW to 40 kW) even though it took 10% more time to undertake the same operation. Thus, using a low-powered smaller tractor reduced the total energy use of the system, thereby saving energy, and increasing energy efficiency on a per hectare basis. However this would increase the labour component, but the effect on profit is unknown.

7.2.3.3 Guidance for further research to improve sustainability of organic orchard systems

The model provided guidance into carrying out further research to improve the sustainability of organic orchard systems in New Zealand. It is acknowledged that when the soil organic matter is mined through agricultural production, the soil’s inherent productivity declines despite the fact that yields can be maintained by adding various soil amendments (USDA, 2003). Soil carbon is used as an indicator of soil organic matter in this research. Sensitivity analysis indicated that the model organic kiwifruit system was sensitive to the rate of CO_2 emissions from the decomposition of organic matter. This suggests a need for further research on how to minimise the release of CO_2 from soil organic matter decomposition in the orchard soil, which will lead to sequestering higher amounts of carbon and improved sustainability.

One of the areas of research aiming to reduce the rate of CO_2 emissions from decomposition looks at converting organic matter into biochar[26] and applying that as a soil amendment (Lehmann, 2007a; IBI, 2008). Lehmann (2007b) demonstrates that 10% of the annual fossil fuel emissions of carbon in the USA could be sequestered annually as biochar either by utilising: (1) 3.5 t/ha of residues or thinnings from 200 million hectares of USA forest land for timber production; or (2) 20 t/ha/yr of fast-growing vegetation from 30 million hectares of idle USA cropland; or (3) 5.5 t/ha/yr of crop residues from 120 million hectares of harvested USA cropland. The study by Lehmann (2007b) suggests that there is a need for research on how the organic matter, e.g., prunings, shelter-trims, and organic

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[26] Biochar is the charcoal produced from biomass through chemical decomposition by burning under anaerobic conditions. Biochar is largely inert and largely resistant to decomposition (Lehmann, 2007a). It is carbon-negative and serves as a net withdrawal of atmospheric carbon dioxide. Biochar is recommended to be applied as soil amendment to enhance soil carbon capture.

material from headlands or other unused areas on the orchard, could be collected and converted into biochar before they are returned to the soil. In theory, this could reduce the CO_2 emissions from decomposition of organic matter in organic orchard soils. However, the energy costs associated with biochar preparation and later its application as a soil amendment also needs to be considered.

7.3 Conclusions

Several important conclusions arise from this research. These conclusions are useful in the development of policy, for improving management practices at the organic orchard system level, for providing insights for the orchard industry, and for providing insights for improving sustainability assessment of orchard systems.

The research conducted in this study reinforces the idea that organic orchard systems should be acknowledged as carbon sinks under the Kyoto Protocol. However, currently the carbon that is captured in the orchard systems does not count under the Kyoto Protocol. Therefore, this research has implications for the horticultural industry as to how well the industry can put forward a case to the government so that orchard crops can be included under New Zealand’s Emission Trading Scheme. At the national policy level, the New Zealand Government can put forward a case to the United Nations Framework Convention on Climate Change to include orchard crops for trading carbon credits. The consideration of orchard crops for trading carbon credits can also have implications for other sectors. For example, part of the area of a pastoral or cropping system can be converted to orchard crops, thus forming carbon sink and increasing the monetary benefits for the whole farm under the ETS.

Sustainability analyses of the organic orchard systems suggest that there are trade-offs within the environmental component. Due to these trade-offs, it is not always possible to recommend concrete areas in management practices to improve the sustainability of organic orchard systems. For example, preparing the compost on the orchard will save energy in transporting the compost; however, it will affect the soil carbon sequestration negatively and would also have impacts on nutrient balances due to the lower input of organic matter. Similarly, maintaining an orchard without a grass-legume understorey might reduce N-leaching to below threshold levels, but might result in a deficiency of N, which can be a threat to yields. However, as the threshold levels are identified, this approach can help in making an informed decision to choose a rationale management option.

Nutrient management is an important issue for organic apple systems in New Zealand and plays an important role in their sustainability. The results of the model suggest that apple growers do not apply adequate potassium, which is a threat to future yields and sustainability. This suggests that there is a need to change the grower behaviour that currently appears to exploit the natural capital by depleting the soil nutrient reserves. Annual applications of compost, in addition to other mineral fertilisers that are permitted under organic certification, have to be supplied to minimise depletion of current soil potassium levels. However, adding these fertilisers might have other associated costs in terms of energy use, CO_2 emissions, and N-leaching, which might have implications on the overall aim to sustainability.

Site selection for orchard establishment is important to achieve overall environmental sustainability of organic orchard systems in New Zealand. This conclusion is important for the horticultural industry which implies that orchards should be located on sites that are most suitable from an environmental sustainability point of view. Orchard location can influence sustainability through the requirement of energy consuming inputs such as irrigation in kiwifruits and frost protection in kiwifruits and apples (management scenario analysis in Chapters 5 and 6), the ability of the soil to supply adequate nutrients and minimise N-leaching. Hence, selecting an appropriate site during the establishment phase of the orchard is important in the overall aim to achieve environmental sustainability.

The application of the model to the organic orchard systems suggests that the model is appropriate for assessing sustainability as it gives results which are consistent with the previous studies, it is able to identify the trade-offs between various indicators, and it suggests improvements in orchard management practices to move towards sustainability. The sustainability assessment approach will further improve as increased understanding into the quantitative relationships between different model components becomes available. This will help to better understand the sustainability of organic orchard systems.

7.4 Recommendations

An important result of developing a sustainability assessment approach such as that undertaken in this research is the development of new perspectives on how to improve the process. The key recommendations from this research are presented below.

It is recommended that other indicators which are consistent with the criteria for socio-economic sustainability could be integrated into the present approach, once environmental criteria are met. The lack of socio-economic indicators in the present approach meant that aspects which might have implications on the financial viability of the systems were not considered. One such aspect is the conversion of fruit yield into fruit energy. The entire fruit yield was converted into energy output using the same energy coefficient, irrespective of variations in size, shape and visual appearance of the fruits. However, these factors play an important role in deciding the selling price for the produce, which will affect the financial sustainability of the orchard system.

The sustainability assessment approach should be applied to study other organic and conventional orchard systems. Application of the proposed sustainability assessment to a range of orchard systems will help attach a greater confidence into the usefulness of this approach as a tool to undertake sustainability assessment of orchard systems. There is no reason why this assessment approach cannot be applied to conventional orchard systems, provided the necessary energy and matter equivalents for the inputs are known from the literature.

The identification of the parameter for soil CO_2 emissions from the decomposition of organic matter in the orchard is an area of research that needs to be explored under orchard crops in New Zealand. The coefficient used in this research was taken from willow energy plantation systems in the UK because no similar information was available for orchard systems. This coefficient may either underestimate or overestimate CO_2 emissions from orchard soils. Orchard crops such as kiwifruits and apples are pruned every year and might return more organic matter in the form of leaves and wood to the soil than the bioenergy plantations which are harvested every 3-5 years. This means that more carbon might be expected to be sequestered in orchards as the carbon input is higher than in the willow bioenergy crop. If this is the case, then the carbon that is estimated to be sequestered in the orchard soil in this research will be underestimated. On the other hand, orchard soils are more exposed to machinery traffic than willow bioenergy plantations, which might release more carbon relative to the carbon input in the orchard crops than the willow bioenergy plantations because of soil disturbance and organic matter oxidation. This might result in overestimation of the carbon sequestered in this research. This suggests that the lack of information on the parameter for soil CO_2 emissions relative to carbon inputs from the orchard crops under New Zealand conditions is a gap in knowledge, which has to be filled through further research.

The threshold level for N-leaching from the orchard soil that can be a potential threat to aquatic ecosystems has to be identified under New Zealand conditions. In this research the threshold value was considered from other studies because values were not available under New Zealand conditions. It is known that the levels of N in water bodies that can have potential adverse effect on the aquatic ecosystem depend on the particular aquatic ecosystem under consideration. Identification of this value for New Zealand conditions will make future policy-making more effective.

Indicators that have positive and negative effects on biodiversity can be integrated into the present model. This especially entails the effect of orchard production practices on biodiversity impacts in relation to the use of copper which can best be addressed by considering at least a time frame of a decade.

Since fossil fuels will be exhausted in some future point in time, the challenge remains for research to develop food production systems with higher yields that rely to a lesser extent on non-renewable energies. Thus, sustainable agriculture may mean redesigning systems to rely on the flow of renewable resources. This means identification of strategies that will systematically reduce the dependence on non-renewable resources in order to progress towards the path to sustainability.

7.5 A final word

Food is a basic need of human beings and agriculture will continue to be an important human activity. Humans can do without fascinating material objects developed by society, but they cannot survive without a sustainable agriculture. Sustainability discussions initially began with a strong emphasis on the natural environment and the concern that humans should be responsible towards environmental protection. However, the concept grew to include socio-economic concerns as well. Although socio-economic concerns are important, sustainability essentially has an environmental bottom line. Failure to understand and live within environmental limits is the main reason for unsustainability.

There is a general consensus that agricultural practices that degrade the environment must change to become more sustainable. This implies that transition to sustainable farming systems requires a change in behaviour on the part of individuals, governments, and institutions to one that recognises the environmental bottom line. Assessment frameworks should be capable of sending signals when the biophysical limits are approached, so that changes required for moving towards sustainability can be managed without undue hardship on individuals or communities. A precondition for fulfilling this aim is the development of practically applicable assessment approaches with indicators that are consistent with the basic scientific underpinnings of sustainability. The assessment approach developed in this research is a step forward to achieving this aim.

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APPENDIX I Interview questionnaire (guide questions)

The interview guidelines are the same for both kiwifruit and apple orchards, except for the first page.

Organic kiwifruit orchard.

Owner name ______________________________

Orchard name ______________________________

Address ______________________________

____

Ph ____________________ Mobile ____________________

Fax ______________________________

Email______________________________

Canopy orchard area ha

Total orchard area ha Soil Type

Irrigated/not irrigated Plant type/rootstock

Plant spacing M/F ratio

Training system

Full organic registration for ------------years Certification agency

Yield total trays/canopy ha Pack-out (no of trays)

Approximate air distance of the apple orchard from the coast (km) (for Overseer)

Organic apple orchard.

Owner name ______

Orchard name ______

Address ______

______

Ph ______ Mobile ______

Fax ______

Email______

Effective orchard area ha	Total orchard area ha
Soil type	Irrigated/not irrigated

	1	2	3	4
Variety mix (name)				
Rootstocks				
Density				
Training system				
Age of trees				

Full organic registration for ------------years Certification agency

YIELD: Total tray carton equivalent OR Total product yield tonnes picked/ha OR Total number of bins /ha (pl. specify bin size)

Approximate air distance of the kiwifruit orchard from the coast (km) (for Overseer)

Please list all equipment/machinery used on your orchard[1]. This includes both that owned by you and that operated by contractors. Machinery is defined as any equipment that use the fuel type/energy sources[3] listed below. Use the assigned equipment/machinery number (column 1) to identify the use of equipment/machinery in the following sections.

[1] all descriptive names/number used by the manufacturer to identify the model

[2] cc rating for engines; pump power (kW)

[3] diesel, petrol, lubricant, batteries, electricity

IF YOU USE A CONTRACTOR, MAY I CONTACT THEM? WHO ARE THEY?

Equipment number	**Description**	**Make**	**Model[1]**	**Rating[2]**	**Fuel/energy type[3]**	**Weight (kgs)**
1						
2						
3						
4						
5…						

Calendar of operations

Spray diaries- Can you please supply copies of your spray diaries from your orchard for the previous 2 seasons.

No.	**Operation (eg. Pruning, spraying, harvesting compost making etc.)**	**Rate of application**	**Equipment (write the column number)**	**No of passes in a year**	**Labour used per bay (hours/day)**	**Time required hours/minutes/ days for the operation**	**Remarks**
	Eg. Winter pruning						
	Spraying for fungicides						
	Mulching etc.						
1							
2							
3							
4							
5…							

Do you make your own compost? Yes/no; Rate of application t/ha

How do you dispose the prunings? eg. mulched/burnt/removed from orchard

How do you manage the under-storey eg. Cover crop/Mowing/Clean cultivation

Irrigation

General description of irrigation system ________________________________

____

Water source: surface water (river, stream, lake) or groundwater (bore, artesian)

____

Pumps and its description such as hp rating. Depth of bore well etc.

> If you know the amount of electricity used to irrigate a known area of your orchard, please record this here (kW*/ha)
> *a meter reading of 100 units = 100kW--

How often is irrigation applied (on a block or total orchard basis)

What do you do to fight frost? Describe in brief the machinery used to fight frost. How many hours do you use it on average in one season?

How far is the pack-house from your orchard?

Can I contact you again in case of missing data? Yes / no

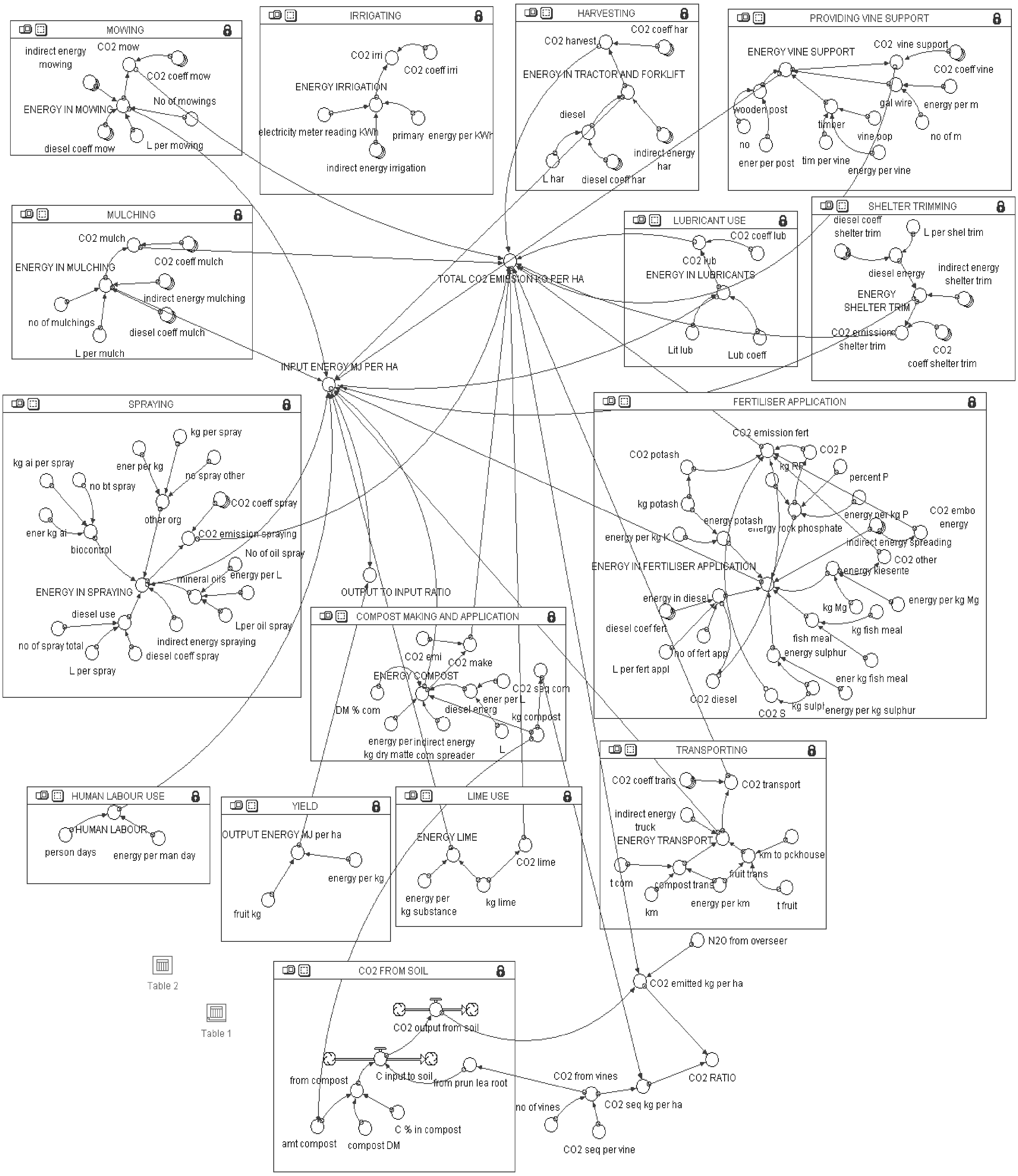
Thank you.

APPENDIX II Composition of fertilisers (%)

Item	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**
Compost	0.3	0.3					
Potassium sulphate			42			18	
Kieserite					18	23	
Patent kali			30		10	42	
Rock phosphate		21		20			
Fish meal	10	6					
Blood and bone	6	6					
Biophos	3.5	1.9	2.3	0.7	0.6	0.3	0.4
Wuxal amino	9.2						
Magnesium sulphate					10		

APPENDIX III Stella® map and equations for the model organic kiwifruit system

The schematic showing all the components of the model organic kiwifruit system considered for sustainability analysis. The individual boxes represent the energy use and CO_2-equivalent emissions from either an operation or a process.



Equations for estimating sustainability indicators for the model organic kiwifruit system

COMPOST
CO2_emi = 0.08
CO2_make = CO2_emi*ENERGY_COMPOST
CO2_seq_com = kg_compost*0.5*0.4*3.67
diesel_energ = ener_per_L*L
DM_%_com = 0.5
ener_per_L = 46.7
ENERGY_COMPOST =
(DM_%_com*energy_per__kg_dry_matter*kg_compost)+indirect_energy__com_spreader+diesel_energ
energy_per__kg_dry_matter = 1.1
indirect_energy__com_spreader = 75
kg_compost = 8000
L = 4

FERTILISER APPLICATION
CO2_diesel = energy_in_diesel*0.08
CO2_embo__energy = indirect_energy_spreading[3]*0.08
CO2_emission_fert =
CO2_diesel+CO2_potash+CO2_other+CO2_P+CO2_S+CO2_embo__energy
CO2_other = energy_kieserite*0.3
CO2_P = energy_rock_phosphate*0.06
CO2_potash = kg_potash*0.6
CO2_S = kg_sulphur*0.3
diesel_coef_fert[diesel_coefficient] = 46.7
ener_kg_fish_meal = 5
energy_in_diesel = diesel_coef_fert[1]*no_of_fert_app*L_per_fert_appl
ENERGY_IN_FERTILISER_APPLICATION =
indirect_energy_spreading[3]+energy_in_diesel+energy_kieserite+energy_potash+energy_rock_phosphate+energy_sulphur+fish_meal
energy_kieserite = energy_per_kg_Mg*kg_Mg
energy_per_kg_K = 10
energy_per_kg_Mg = 5
energy_per_kg_P = 15
energy_per_kg_sulphur = 5
energy_potash = energy_per_kg_K*kg_potash
energy_rock_phosphate = energy_per_kg_P*kg_RP*percent_P
energy_sulphur = energy_per_kg_sulphur*kg_sulphur
fish_meal = ener_kg_fish_meal*kg_fish_meal
indirect_energy_spreading[embodied_energy] = 716
kg_fish_meal = 0
kg_Mg = 54
kg_potash = 82
kg_RP = 250
kg_sulphur = 105

L_per_fert_appl = 4.72
no_of_fert_app = 4
percent_P = 0.21

FROST FIGHTING

CO2__frost = CO2_coeff_frost[1]*ENERGY_IN_FROST_FIGHTING
CO2_coeff_frost[CO2_coefficient] = 0.08
diesel_coeff_frost[diesel_coefficient] = 46.7
ENERGY_IN_FROST_FIGHTING = total_diesel_use+indirect_energy__per_year[3]
indirect_energy__per_year[embodied_energy] = 1280
L__per_hr_frost = 4
no_of_hours = 40
total_diesel_use = diesel_coeff_frost[1]*L__per_hr_frost*no_of_hours

CO2 FROM SOIL

UNATTACHED:
C_input_to_soil = from_compost+from_prun_lea_root
UNATTACHED:
CO2_output_from_soil = C_input_to_soil*0.82*3.67
amt_compost = kg_compost
C_%_in_compost = 0.4
compost_DM = 0.5
from_compost = amt_compost*C_%_in_compost*compost_DM
from_prun_lea_root = CO2_from_vines*0.55/3.67

HARVESTING

CO2_coeff_har[CO2_coefficient] = 0.08
CO2_harvest = CO2_coeff_har[1]*ENERGY_IN_TRACTOR_AND_FORKLIFT
diesel = L_har*diesel_coeff_har[1]
diesel_coeff_har[diesel_coefficient] = 46.7
ENERGY_IN_TRACTOR_AND_FORKLIFT = diesel+indirect_energy__har[3]
indirect_energy__har[embodied_energy] = 757
L_har = 24.3

IRRIGATING

CO2_coeff_irri = 0.06
CO2_irri = CO2_coeff_irri*ENERGY_IRRIGATION
electricity_meter_reading_KWh = 895
ENERGY_IRRIGATION = indirect_energy_irrigation[3]+(electricity_meter_reading_KWh*primary__energy_per_KWh)
indirect_energy_irrigation[embodied_energy] = 1272
primary__energy_per_KWh = 7.5

HUMAN LABOUR USE

energy_per_man_day = 18.3
HUMAN_LABOUR = energy_per_man_day*person_days
person_days = 70

LIME USE

CO2_lime = kg_lime*0.43
ENERGY_LIME = energy_per__kg_substance*kg_lime
energy_per__kg_substance = 0.6
kg_lime = 500

LUBRICANT USE

CO2_coeff_lub = 0.04
CO2_lub = ENERGY_IN_LUBRICANTS*CO2_coeff_lub
ENERGY_IN_LUBRICANTS = Lub_coeff*Lit_lub
Lit_lub = 7.7
Lub_coeff = 49.2

MOWING

CO2_coeff_mow[CO2_coefficient] = 0.08
CO2_mow = CO2_coeff_mow[1]*ENERGY_IN_MOWING
diesel_coeff_mow[diesel_coefficient] = 46.7
ENERGY_IN_MOWING = indirect_energy__mowing[3]+(diesel_coeff_mow[1]*L_per_mowing*No_of_mowings)
indirect_energy__mowing[embodied_energy] = 1816
L_per_mowing = 8.69
No_of_mowings = 6

MULCHING

CO2_coeff_mulch[CO2_coefficient] = 0.08
CO2_mulch = CO2_coeff_mulch[1]*ENERGY_IN_MULCHING
diesel_coeff_mulch[diesel_coefficient] = 46.7
ENERGY_IN_MULCHING = indirect_energy_mulching[3]+(L_per_mulch*diesel_coeff_mulch[1]*no_of_mulchings)
indirect_energy_mulching[embodied_energy] = 1786
L_per_mulch = 14.17
no_of_mulchings = 3

SHELTER TRIMMING

CO2__coeff_shelter_trim[CO2_coefficient] = 0.08
CO2_emission__shelter_trim = CO2__coeff_shelter_trim[1]*ENERGY__SHELTER_TRIM
diesel_coeff__shelter_trim[CO2_coefficient] = 46.7
diesel_energy = diesel_coeff__shelter_trim[1]*L_per_shel_trim
ENERGY__SHELTER_TRIM = diesel_energy+indirect_energy__shelter_trim[3]
indirect_energy__shelter_trim[embodied_energy] = 243
L_per_shel_trim = 10.5

SPRAYING

biocontrol = ener_kg_bt*kg_bt_per_spray*no_bt_spray
CO2_coeff_spray[CO2_coefficient] = 0.08

CO2_emission_spraying = CO2_coeff_spray[1]*ENERGY_IN_SPRAYING
diesel_coeff_spray = 46.7
diesel_use = diesel_coeff_spray*L_per_spray*no_of_spray_total
ener_kg_material = 120
ener_per_kg = 5
ENERGY_IN_SPRAYING = biocontrol+diesel_use+indirect_energy_spraying+mineral_oils+other_org
energy_per_L = 29
indirect_energy_spraying = 2017
kg_ai_per_spray = 0.4
kg_per_spray = 176
L_per_spray = 7.08
Lper_oil_spray = 15
mineral_oils = energy_per_L*Lper_oil_spray*No_of_oil_spray
no_bt_spray = 2
No_of_oil_spray = 2
no_of_spray_total = 7
no_spray_other = 2
other_org = ener_per_kg*no_spray_other*kg_per_spray

TRANSPORTING
CO2_coeff_trans[CO2_coefficient] = 0.08
CO2_transport = CO2_coeff_trans[1]*ENERGY_TRANSPORT
compost_trans = km*energy_per_km*t_com
energy_per_km = 3
ENERGY_TRANSPORT = compost_trans+indirect_energy__truck+fruit_trans
fruit_trans = energy_per_km*km_to_pckhouse*t_fruit
indirect_energy__truck = 711
km = 100
km_to_pckhouse = 15
t_com = 8
t_fruit = 21

PROVIDING VINE SUPPORT
CO2__vine_support = CO2_coeff_vine[1]*ENERGY_VINE_SUPPORT
CO2_coeff_vine[CO2_coefficient] = 0.08
ener_per_post = 18
energy_per_m = 1.3
energy_per_vine = 3.45
ENERGY_VINE_SUPPORT = (gal_wire+timber+wooden_post)/20
gal_wire = energy_per_m*no_of_m
no = 80
no_of_m = 20000
tim_per_vine = 4.6
timber = energy_per_vine*tim_per_vine*vine_pop
vine_pop = 500
wooden_post = ener_per_post*no

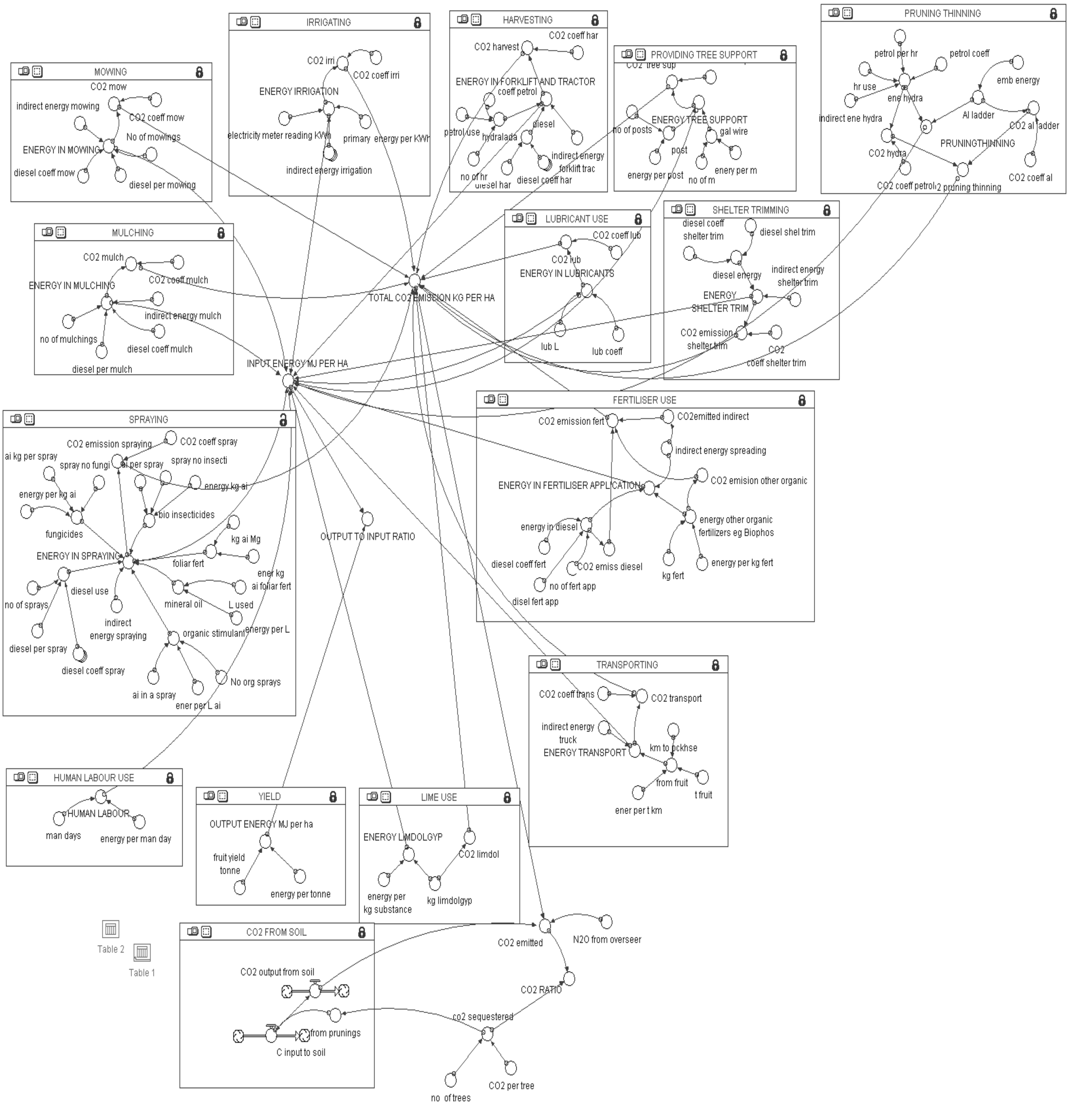
YIELD

energy_per_kg = 2.55
fruit_kg = 21000
OUTPUT_ENERGY_MJ_per_ha = energy_per_kg*fruit_kg

Not in a sector
CO2_emitted_kg_per_ha = TOTAL_CO2_EMISSION_KG_PER_HA+N2O_from_overseer+CO2_output_from_soil
CO2_from_vines = CO2_seq_per_vine*no_of_vines
CO2_RATIO = CO2_seq_kg_per_ha/CO2_emitted_kg_per_ha
CO2_seq_kg_per_ha = CO2_from_vines+CO2_seq_com
CO2_seq_per_vine = 27.46
INPUT_ENERGY_MJ_PER_HA = ENERGY_COMPOST+ENERGY_IN_FERTILISER_APPLICATION+ENERGY_IN_TRACTOR_AND_FORKLIFT+ENERGY_IN_LUBRICANTS+ENERGY_IN_MOWING+ENERGY_IN_MULCHING+ENERGY_IN_SPRAYING+ENERGY_LIME+ENERGY_TRANSPORT+ENERGY_VINE_SUPPORT+HUMAN_LABOUR+ENERGY__SHELTER_TRIM
N2O_from_overseer = 249
no_of_vines = 500
OUTPUT_TO_INPUT_RATIO = OUTPUT_ENERGY_MJ_per_ha/INPUT_ENERGY_MJ_PER_HA
TOTAL_CO2_EMISSION_KG_PER_HA = CO2__vine_support+CO2_emission_fert+CO2_emission_spraying+CO2_harvest+CO2_lub+CO2_make+CO2_mow+CO2_mulch+CO2_transport+CO2_emission__shelter_trim+CO2_lime

APPENDIX IV Stella® map and equations for the model organic semi-intensive apple system

The schematic showing all the components of the model organic semi-intensive apple system considered for sustainability analysis. The individual boxes represent energy use and CO_2-equivalent emissions from either an operation or a process.



Equations for estimating sustainability indicators for the model organic semi-intensive apple system

FERTILISER APPLICATION
CO2_emision_other_organic = energy_other_organic_fertilizers_eg_Biophos*0.08
CO2_emiss_diesel = energy_in_diesel*0.08
CO2_emission_fert =
CO2_emiss_diesel+CO2_emision_other_organic+CO2emitted_indirect
CO2emitted_indirect = indirect_energy_spreading*0.08
diesel_coeff_fert = 46.7
disel_fert_app = 6.3
energy_in_diesel = diesel_coeff_fert*disel_fert_app*no_of_fert_app
ENERGY_IN_FERTILISER_APPLICATION =
indirect_energy_spreading+energy_in_diesel+energy_other_organic_fertilizers_eg_Biophos
energy_other_organic_fertilizers_eg_Biophos = energy_per_kg_fert*kg_fert
energy_per_kg_fert = 5
indirect_energy_spreading = 245
kg_fert = 500
no_of_fert_app = 2

CO2 FROM SOIL
UNATTACHED:
C_input_to_soil = from_prunings
UNATTACHED:
CO2_output_from_soil = C_input_to_soil*0.82*3.67
from_prunings = co2_sequestered*0.76/3.67

HARVESTING
CO2_coeff_har = 0.08
CO2_harvest = CO2_coeff_har*ENERGY_IN_FORKLIFT_AND_TRACTOR
coeff_petrol = 42.3
diesel = diesel_har*diesel_coeff_har[1]
diesel_coeff_har[diesel_coefficient] = 46.7
diesel_har = 39.5
ENERGY_IN_FORKLIFT_AND_TRACTOR =
diesel+indirect_energy__forklift_trac+hydralada
hydralada = coeff_petrol*no_of_hr*petrol_use
indirect_energy__forklift_trac = 2489
no_of_hr = 16
petrol_use = 2

IRRIGATING
CO2_coeff_irri = 0.06
CO2_irri = CO2_coeff_irri*ENERGY_IRRIGATION
electricity_meter_reading_KWh = 1180
ENERGY_IRRIGATION =
indirect_energy_irrigation[9]+(electricity_meter_reading_KWh*primary__energy_per_KWh)

indirect_energy_irrigation[embodied_energy] = 1219
primary__energy_per_KWh = 7.5

HUMAN LABOUR USE
energy_per_man_day = 18.3
HUMAN_LABOUR = energy_per_man_day*man_days
man_days = 110

LIME USE
CO2_limdol = kg_limdolgyp*0.43
ENERGY_LIMDOLGYP = energy_per__kg_substance*kg_limdolgyp
energy_per__kg_substance = 0.6
kg_limdolgyp = 300

LUBRICANT USE
CO2_coeff_lub = 0.04
CO2_lub = ENERGY_IN_LUBRICANTS*CO2_coeff_lub
ENERGY_IN_LUBRICANTS = lub_coeff*lub_L
lub_coeff = 49.2
lub_L = 18

MOWING
CO2_coeff_mow = 0.08
CO2_mow = CO2_coeff_mow*ENERGY_IN_MOWING
diesel_coeff_mow = 46.7
diesel_per_mowing = 7.8
ENERGY_IN_MOWING =
indirect_energy_mowing+(diesel_coeff_mow*diesel_per_mowing*No_of_mowings)
indirect_energy_mowing = 737
No_of_mowings = 6

MULCHING
CO2_coeff_mulch = 0.08
CO2_mulch = CO2_coeff_mulch*ENERGY_IN_MULCHING
diesel_coeff_mulch = 46.7
diesel_per_mulch = 21
ENERGY_IN_MULCHING =
(diesel_coeff_mulch*diesel_per_mulch*no_of_mulchings)+indirect_energy_mulch
indirect_energy_mulch = 527
no_of_mulchings = 1

PRUNING THINNING
Al_ladder = emb_energy
CO2_al_ladder = Al_ladder*CO2_coeff_al
CO2_coeff_al = 0.08
CO2_coeff_petrol = 0.075
CO2_hydra = CO2_coeff_petrol*ene_hydra
CO2_hydra_al = CO2_hydra+CO2_al_ladder

emb_energy = 147
ene_hydra = (hr_use*petrol_per_hr*petrol_coeff)+indirect_ene_hydra
hr_use = 42
indirect_ene_hydra = 1275
petrol_coeff = 42.3
petrol_per_hr = 2
PRUNINGTHINNING = Al_ladder+ene_hydra

SHELTER TRIMMING
CO2__coeff_shelter_trim = 0.08
CO2_emission__shelter_trim =
CO2__coeff_shelter_trim*ENERGY__SHELTER_TRIM
diesel_coeff__shelter_trim = 46.7
diesel_energy = diesel_coeff__shelter_trim*diesel_shel_trim
diesel_shel_trim = 10.5
ENERGY__SHELTER_TRIM = diesel_energy+indirect_energy__shelter_trim
indirect_energy__shelter_trim = 243

SPRAYING
ai_in_a_spray = 67.5
ai_kg_per_spray = 2.24
ai_per_spray = 0.09
bio_insecticides = ai_per_spray*energy_kg_ai*spray_no_insecti
CO2_coeff_spray = 0.08
CO2_emission_spraying = CO2_coeff_spray*ENERGY_IN_SPRAYING
diesel_coeff_spray[diesel_coefficient] = 46.7
diesel_per_spray = 6.3
diesel_use = diesel_coeff_spray[1]*diesel_per_spray*no_of_sprays
ener_kg__ai_foliar_fert = 10
ener_per_L_ai = 5
ENERGY_IN_SPRAYING =
bio_insecticides+diesel_use+indirect__energy_spraying+foliar_fert+fungicides+mineral_oil+organic_stimulants
energy_kg_ai = 120
energy_per_kg_ai = 111.47
energy_per_L = 29.9
foliar_fert = ener_kg__ai_foliar_fert*kg_ai_Mg
fungicides = ai_kg_per_spray*energy_per_kg_ai*spray_no_fungi
indirect__energy_spraying = 2065
kg_ai_Mg = 0.01
L_used = 20
mineral_oil = energy_per_L*L_used
no_of_sprays = 29
No_org_sprays = 2
organic_stimulants = ai_in_a_spray*ener_per_L_ai*No_org_sprays
spray_no_fungi = 18
spray_no_insecti = 10

TRANSPORTING
CO2_coeff_trans = 0.08
CO2_transport = CO2_coeff_trans*ENERGY_TRANSPORT
ener_per_t_km = 3
ENERGY_TRANSPORT = indirect_energy__truck+from_fruit
from_fruit = ener_per_t_km*km_to_pckhse*t_fruit
indirect_energy__truck = 711
km_to_pckhse = 10
t_fruit = 36.9

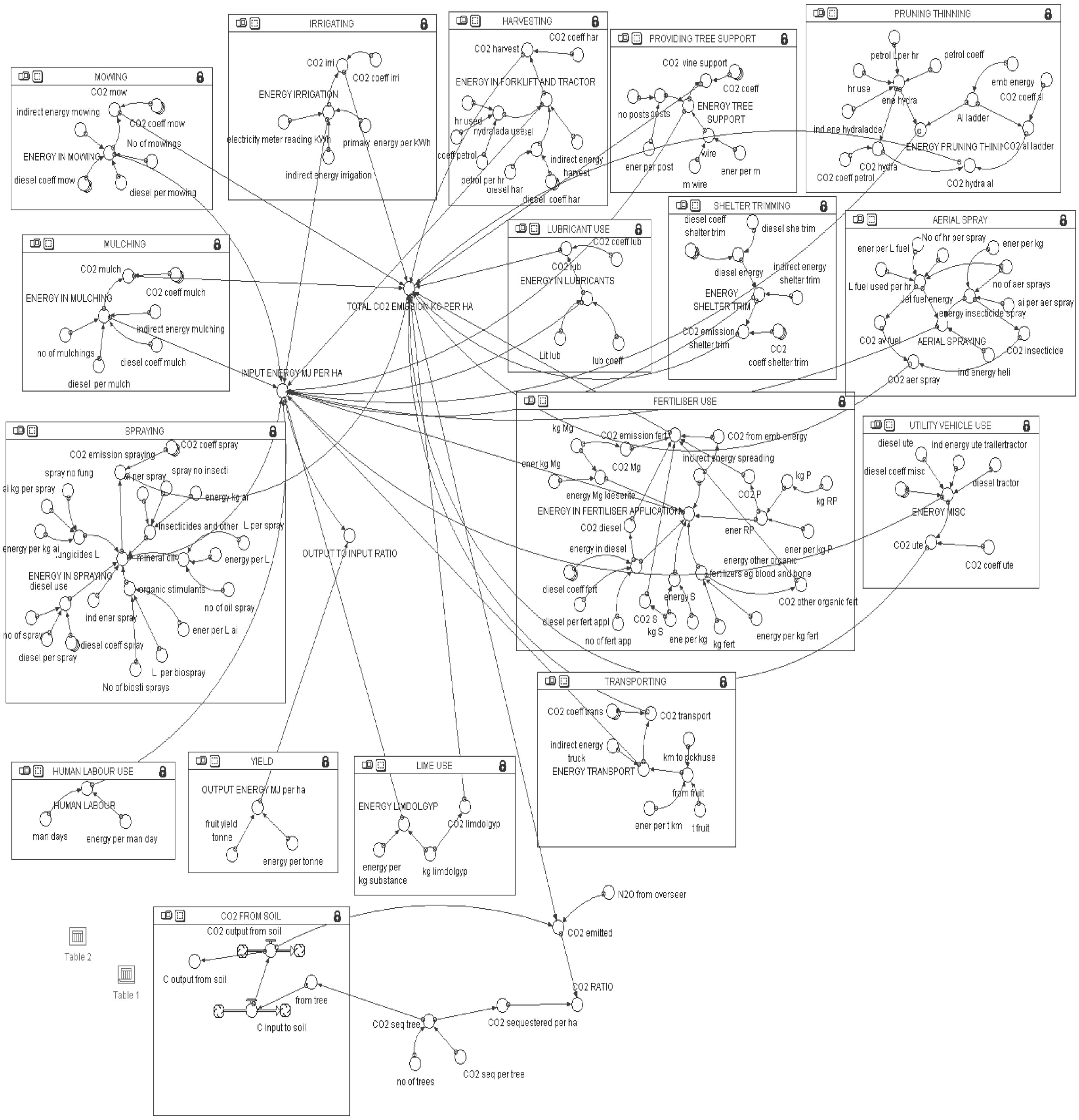
PROVIDING TREE SUPPORT
CO2__tree_sup = CO2_coeff_tree_sup*ENERGY_TREE_SUPPORT
CO2_coeff_tree_sup = 0.08
energy_per_post = 18
ENERGY_TREE_SUPPORT = (gal_wire+post)/20
enery_per_m = 1.3
gal_wire = enery_per_m*no_of_m
no_of_m = 4000
no_of_posts = 200
post = energy_per_post*no_of_posts

YIELD
energy_per_tonne = 2180
fruit_yield__tonne = 36.9
OUTPUT_ENERGY_MJ_per_ha = energy_per_tonne*fruit_yield__tonne

Not in a sector
CO2_emitted = CO2_output_from_soil+N2O_from_overseer+TOTAL_CO2_EMISSION_KG_PER_HA
CO2_per_tree = 29.47
CO2_RATIO = co2_sequestered/CO2_emitted
co2_sequestered = no__of_trees*CO2_per_tree
INPUT_ENERGY_MJ_PER_HA = ENERGY_IN_FERTILISER_APPLICATION+ENERGY_IN_FORKLIFT_AND_TRACTOR+ENERGY_IN_LUBRICANTS+ENERGY_IN_MOWING+ENERGY_IN_MULCHING+ENERGY_IN_SPRAYING+ENERGY_LIMDOLGYP+ENERGY_TRANSPORT+HUMAN_LABOUR+ENERGY__SHELTER_TRIM+ENERGY_IRRIGATION+PRUNINGTHINNING+ENERGY_TREE_SUPPORT
N2O_from_overseer = 394
no__of_trees = 800
OUTPUT_TO_INPUT_RATIO = OUTPUT_ENERGY_MJ_per_ha/INPUT_ENERGY_MJ_PER_HA
TOTAL_CO2_EMISSION_KG_PER_HA = CO2_transport+CO2_emission_fert+CO2_harvest+CO2_lub+CO2_mow+CO2_emission_spraying+CO2_limdol+CO2_emission__shelter_trim+CO2_irri+CO2_mulch+CO2__tree_sup+CO2_hydra_al

APPENDIX V Stella® map and equations for the model organic intensive apple system

The schematic showing all the components of the model organic intensive apple system considered for sustainability analysis. The individual boxes represent energy use and CO_2-equivalent emissions from either an operation or a process.



Equations for estimating sustainability indicators for the model organic intensive apple system

AERIAL SPRAY

AERIAL_SPRAYING = ind_energy_heli+Jet_fuel_energy+energy_insecticide_spray
ai_per_aer_spray = 0.08
CO2_aer_spray = CO2_av_fuel+CO2_insecticide
CO2_av_fuel = Jet_fuel_energy*0.068
CO2_insecticide = energy_insecticide_spray*0.08
ener_per_kg = 120
ener_per_L_fuel = 35.06
energy_insecticide_spray = ai_per_aer_spray*ener_per_kg*no_of_aer_sprays
ind_energy_heli = 26
Jet_fuel_energy = ener_per_L_fuel*L_fuel_used_per_hr*No_of_hr_per_spray*no_of_aer_sprays
L_fuel_used_per_hr = 100
no_of_aer_sprays = 3
No_of_hr_per_spray = 0.06

FERTILISER APPLICATION

CO2_diesel = energy_in_diesel*0.08
CO2_emission_fert = CO2_diesel+CO2_other_organic_fert+CO2_P+CO2_from_emb_energy+CO2_Mg+CO2_S
CO2_from_emb_energy = indirect_energy_spreading*0.08
CO2_Mg = kg_Mg*0.6
CO2_other_organic_fert = energy_other_organic_fertilizers_eg_blood_and_bone*0.08
CO2_P = ener_RP*0.06
CO2_S = kg_S*0.3
diesel_coeff_fert[diesel_coefficient] = 46.7
diesel_per_fert_appl = 7.87
ene_per_kg = 5
ener_kg_Mg = 15
ener_per_kg_P = 15
ener_RP = ener_per_kg_P*kg_P
energy_in_diesel = diesel_coeff_fert[1]*no_of_fert_app*diesel_per_fert_appl
ENERGY_IN_FERTILISER_APPLICATION = indirect_energy_spreading+ener_RP+energy_in_diesel+energy_other_organic_fertilizers_eg_blood_and_bone+energy_S+energy_Mg_kieserite
energy_Mg_kieserite = ener_kg_Mg*kg_Mg
energy_other_organic_fertilizers_eg_blood_and_bone = energy_per_kg_fert*kg_fert
energy_per_kg_fert = 5
energy_S = ene_per_kg*kg_S
indirect_energy_spreading = 104

kg_fert = 400
kg_Mg = 51
kg_P = kg_RP*0.21
kg_RP = 0
kg_S = 0
no_of_fert_app = 3

FROST FIGHTING

CO2__frost = CO2_coeff_frost[1]*ENERGY_IN_FROST_FIGHTING
CO2_coeff_frost[CO2_coefficient] = 0.08
diesel_coeff_frost[diesel_coefficient] = 46.7
ENERGY_IN_FROST_FIGHTING = indirect_energy__per_year+total_diesel_energy
indirect_energy__per_year = 472
L_diesel_per_hr = 4
No_of_hrs = 70
total_diesel_energy = diesel_coeff_frost[1]*L_diesel_per_hr*No_of_hrs

CO2 FROM SOIL

UNATTACHED:
C_input_to_soil = from_tree
UNATTACHED:
CO2_output_from_soil = C_input_to_soil*0.82*3.67
C_output_from_soil = CO2_output_from_soil/3.67
from_tree = (CO2_seq_tree*.76)/3.67

HARVESTING

CO2_coeff_har = 0.08
CO2_harvest = CO2_coeff_har*ENERGY_IN_FORKLIFT_AND_TRACTOR
coeff_petrol = 43.2
diesel = diesel_har*diesel__coeff_har[1]
diesel__coeff_har[diesel_coefficient] = 46.7
diesel_har = 51.71
ENERGY_IN_FORKLIFT_AND_TRACTOR = indirect_energy__harvest+diesel+hydralada_use
hr_used = 20
hydralada_use = coeff_petrol*hr_used*petrol_per_hr
indirect_energy__harvest = 963
petrol_per_hr = 2

IRRIGATING

CO2_coeff_irri = 0.06
CO2_irri = CO2_coeff_irri*ENERGY_IRRIGATION
electricity_meter_reading_KWh = 1180
ENERGY_IRRIGATION = indirect_energy_irrigation+(electricity_meter_reading_KWh*primary__energy_per_KWh)
indirect_energy_irrigation = 1384
primary__energy_per_KWh = 7.5

HUMAN LABOUR USE
energy_per_man_day = 18
HUMAN_LABOUR = energy_per_man_day*man_days
man_days = 95

LIME USE
CO2_limdolgyp = kg_limdolgyp*0.43
ENERGY_LIMDOLGYP = energy_per__kg_substance*kg_limdolgyp
energy_per__kg_substance = 0.6
kg_limdolgyp = 500

LUBRICANT USE
CO2_coeff_lub = 0.04
CO2_lub = ENERGY_IN_LUBRICANTS*CO2_coeff_lub
ENERGY_IN_LUBRICANTS = lub_coeff*Lit_lub
Lit_lub = 23
lub_coeff = 49.2

UTILITY VEHICLE USE
CO2_coeff_ute = 0.08
CO2_ute = CO2_coeff_ute*ENERGY_MISC
diesel_coeff_misc[diesel_coefficient] = 46.7
diesel_tractor = 5
diesel_ute = 5
ENERGY_MISC =
ind_energy_ute_trailertractor+(diesel_coeff_misc[1])*(diesel_tractor+diesel_ute)
ind_energy_ute_trailertractor = 338

MOWING
CO2_coeff_mow[CO2_coefficient] = 0.08
CO2_mow = CO2_coeff_mow[1]*ENERGY_IN_MOWING
diesel_coeff_mow[diesel_coefficient] = 46.7
diesel_per_mowing = 10.5
ENERGY_IN_MOWING =
indirect_energy_mowing+(diesel_coeff_mow[1]*diesel_per_mowing*No_of_mowings)
indirect_energy_mowing = 222
No_of_mowings = 4

MULCHING
CO2_coeff_mulch[CO2_coefficient] = 0.08
CO2_mulch = CO2_coeff_mulch[1]*ENERGY_IN_MULCHING
diesel__per_mulch = 26.25
diesel_coeff_mulch[diesel_coefficient] = 46.7
ENERGY_IN_MULCHING =
indirect_energy_mulching+(diesel__per_mulch*diesel_coeff_mulch[1]*no_of_mulchings)

indirect_energy_mulching = 163
no_of_mulchings = 1

PRUNING THINNING
Al_ladder = emb_energy
CO2_al_ladder = Al_ladder*CO2_coeff_al
CO2_coeff_al = 0.08
CO2_coeff_petrol = 0.07
CO2_hydra = CO2_coeff_petrol*ene_hydra
CO2_hydra_al = CO2_al_ladder+CO2_hydra
emb_energy = 60
ene_hydra = (hr_use*petrol_Lper_hr*petrol_coeff)+ind_ene_hydraladde
ENERGY_PRUNING_THINING = Al_ladder+ene_hydra
hr_use = 47
ind_ene_hydraladde = 883
petrol_coeff = 42.3
petrol_Lper_hr = 2

SHELTER TRIMMING
CO2__coeff_shelter_trim[CO2_coefficient] = 0.08
CO2_emission__shelter_trim = CO2__coeff_shelter_trim[1]*ENERGY__SHELTER_TRIM
diesel_coeff__shelter_trim[CO2_coefficient] = 46.7
diesel_energy = diesel_coeff__shelter_trim[1]*diesel_she_trim
diesel_she_trim = 10.5
ENERGY__SHELTER_TRIM = diesel_energy+indirect_energy__shelter_trim
indirect_energy__shelter_trim = 243

SPRAYING
ai_kg_per_spray = 3.44
ai_per_spray = 0.12
CO2_coeff_spray[CO2_coefficient] = 0.08
CO2_emission_spraying = CO2_coeff_spray[1]*ENERGY_IN_SPRAYING
diesel_coeff_spray[diesel_coefficient] = 46.7
diesel_per_spray = 7.87
diesel_use = diesel_coeff_spray[1]*diesel_per_spray*no_of_sprays
ener_per_L_ai = 8.572
ENERGY_IN_SPRAYING = diesel_use+ind_ener_spray+fungicides_L+insecticides_and_other+organic_stimulants+mineral_oil
energy_kg_ai = 120
energy_per_kg_ai = 111.47
energy_per_L = 30
fungicides_L = spray_no_fung*energy_per_kg_ai*ai_kg_per_spray
ind_ener_spray = 966
insecticides_and_other = ai_per_spray*energy_kg_ai*spray_no_insecti
L__per_biospray = 7.02
L_per_spray = 40
mineral_oil = energy_per_L*L_per_spray*no_of_oil_spray

No_of_biosti_sprays = 2
no_of_oil_spray = 2
no_of_sprays = 35
organic_stimulants = ener_per_L_ai*L__per_biospray*No_of_biosti_sprays
spray_no_fung = 28
spray_no_insecti = 3

TRANSPORTING
CO2_coeff_trans[CO2_coefficient] = 0.08
CO2_transport = CO2_coeff_trans[1]*ENERGY_TRANSPORT
ener_per_t_km = 3
ENERGY_TRANSPORT = indirect_energy__truck+from_fruit
from_fruit = ener_per_t_km*t_fruit*km_to_pckhuse
indirect_energy__truck = 711
km_to_pckhuse = 15
t_fruit = 54

PROVDING TREE SUPPORT
CO2__vine_support = CO2_coeff[1]*ENERGY_TREE__SUPPORT
CO2_coeff[CO2_coefficient] = 0.08
ener_per_m = 1.3
ener_per_post = 18
ENERGY_TREE__SUPPORT = (posts+wire)/20
m_wire = 5000
no_posts = 225
posts = ener_per_post*no_posts
wire = ener_per_m*m_wire

YIELD
energy_per_tonne = 2180
fruit_yield__tonne = 54
OUTPUT_ENERGY_MJ_per_ha = energy_per_tonne*fruit_yield__tonne

Not in a sector
CO2_emitted = CO2_output_from_soil+N2O_from_overseer+TOTAL_CO2_EMISSION_KG_PER_HA
CO2_RATIO = CO2_sequestered_per_ha/CO2_emitted
CO2_seq_per_tree = 21.05
CO2_seq_tree = CO2_seq_per_tree*no_of_trees
CO2_sequestered_per_ha = CO2_seq_tree
INPUT_ENERGY_MJ_PER_HA = ENERGY_IN_FERTILISER_APPLICATION+ENERGY_IN_FORKLIFT_AND_TRACTOR+ENERGY_IN_LUBRICANTS+ENERGY_IN_MOWING+ENERGY_IN_MULCHING+ENERGY_IN_SPRAYING+ENERGY_LIMDOLGYP+ENERGY_TRANSPORT+ENERGY_TREE__SUPPORT+HUMAN_LABOUR+ENERGY__SHELTER_TRIM+ENERGY_IRRIGATION+AERIAL_SPRAYING+ENERGY_PRUNING_THINING+ENERGY_MISC
N2O_from_overseer = 122

no_of_trees = 1250
OUTPUT_TO_INPUT_RATIO = OUTPUT_ENERGY_MJ_per_ha/INPUT_ENERGY_MJ_PER_HA
TOTAL_CO2_EMISSION_KG_PER_HA = CO2_transport+CO2_emission_fert+CO2_harvest+CO2_lub+CO2_mow+CO2_mulch+CO2_emission_spraying+CO2__vine_support+CO2_limdolgyp+CO2_emission__shelter_trim+CO2_irri+CO2_hydra_al+CO2_ute+CO2_aer_spray

APPENDIX VI Embodied energy in irrigation/frost protection system

The following information explains in detail the estimation of embodied energy in irrigation system for the three model systems and the frost protection system (which is the same for all the systems when this operation is used).

Description of irrigation system

The energy associated with orchard irrigation is a combination of well drilling, pumping equipment, pipe-trenching and pipe (Barber & Scarrow, 2001; Wells, 2001; Saunders et al., 2006) as presented in the methodology.

The total embodied energy in the irrigation system in kiwifruit and apple orchards is determined as follows (values are rounded to whole numbers).

Embodied energy in irrigation system – in kiwifruit orchard

Well

Well drilling is estimated to have an energy cost of 400MJ/m (Wells, 1998). It is assumed that there is one 4inch bore with a depth of 20m. Therefore the embodied energy is 400 x 25 = 10000. Allocating over a life of 100 years and the working area of 5 ha, the embodied energy comes to 20 MJ/ha/yr.

Pumps

The embodied energy for pumps is 160 MJ/kg. The weight of pump is assumed to be 40kg. Therefore the embodied energy in pump is 160 x 40 = 6400 with a life of 15 years and working area of 5 ha. Therefore, embodied energy in pump is 85 MJ/ha/yr.

Pipe

The pipe is a combination of a mainline, sub-main and laterals (Saunders et al., 2006).

Mainline: the mainline is assumed to be 20 per cent longer than the cropped orchard width which is 120m/ha. The pipe is 65mm PVC at a weight of 0.74 kg/m. The total embodied energy in PVC is 120 MJ/kg. Therefore, for 120 m = 120 x 0.74 = 89 kg. The total embodied energy is therefore 120 x 89 = 10680 MJ. Allocated over 40 years life, the embodied energy is 267 MJ/ha/yr.

Sub-main

Sub-main is the same width as the orchard which is 100 m/ha. The sub-main is 50 mm PVC pipe at a weight of 0.51 kg/m. It comes to 51 kg/ha. The total embodied energy is 6120 MJ/ha. Allocated over 40 years life, the embodied energy comes to 153 MJ/ha/yr

Lateral

The lateral pipe is 16mm semi-intensive polyethylene (LDPE). The length is equal to total row length which is 2000 m/ha. At a weight of 0.07 kg/m and an embodied energy of 160 MJ/kg the total embodied energy is 22400 MJ/ha. Allocated over 30 year life, the embodied energy comes to 747 MJ/ha/yr.

The total embodied energy per ha per year is the summation of the above:

20+85+267+153+747= 1272 MJ/ha/yr.

Embodied energy in irrigation system – in apple

Both the model systems are irrigated with ground water. Water is pumped from a well at the depth of 30 m. The well is fixed with an electric pump and weighed 40 kg. There is one bore-well of 10 cm in semi-intensive system and a total of four bore-wells in the intensive system, one on each block.

The length of pipes is dependent on the block size and shape and its proximity to the well. Pipe is a combination of the mainline, sub-mains and laterals. For both the systems it is assumed that a block is 100 m x 100 m. There are 20 rows/ha in the semi-intensive system and 25 rows/ha in the intensive system. The mainline is assumed to be 20 percent longer than the block which gives the length of mainline to be 120 m/ha. The sub-main is the same width as the block and is 100 m/ha. Lateral pipe is equal to the row length which is 2000 m for the intensive system and 2500 m for the semi-intensive system. The embodied is estimated as follows:

Embodied energy in irrigation system – in semi-intensive system

Well

Well drilling is estimated to have an energy cost of 400 MJ/m (Wells, 1998). It is assumed that there is one 4inch bore with a depth of 25 m. Therefore the embodied energy is 400 x 25 = 10000. Assuming the life of a well to be 100 years, the embodied energy is 10 MJ/ha/yr.

Pumps

The embodied energy for pumps is 160 MJ/kg. The weight of pump is assumed to be 40 kg. The total embodied energy in pump is 160 x 40 = 6400. Allocated over a life of 15 years and area of 10 ha, it comes to 43 MJ/ha/yr.

Pipe

The pipe is a combination of a mainline, sub-main and laterals (Saunders et al., 2006).

Mainline: the mainline is assumed to be 20 percent longer than the cropped orchard width which is 120 m/ha. The pipe is 65 mm PVC at a weight of 0.74 kg/m. The embodied energy coefficient in mainline is 120 MJ/kg. The embodied energy in mainline is 10680 MJ/ha. Allocated over 40 year life, the embodied energy comes to 267 MJ/ha/yr.

Sub-main

Sub-main is the same width as the orchard and is 100 m/ha. The sub-main is 50mm PVC pipe at a weight of 0.51 kg/m. It comes to a 51 kg/ha. The embodied energy coefficient of sub-main is 120 MJ/kg. The embodied energy in sub-main is 6120 MJ/ha. Allocated over 40 year life of the pipe, the embodied energy comes to 153 MJ/ha/yr

Lateral

The lateral pipe is 16mm semi-intensive polyethylene (LDPE). The length is equal to total row length which is 2000m/ha. At a weight of 0.07 kg/m and an embodied energy of 160 MJ/kg, the total embodied energy is 22400 MJ/ha. Allocated over a 30 year life, the embodied energy comes to 747 MJ/ha/yr.

The total embodied energy per ha per year is the summation of the above:

10+43+267+153+747= 1220 MJ/ha/yr.

Embodied energy in irrigation system – in intensive system

An intensive orchard is 65 ha divided into 4 blocks. Every block has irrigation.

Wells

Well drilling is estimated to have an energy cost of 400 MJ/m (Wells, 1998). It is assumed that there is one 4 inch bore with a depth of 25 m in all four blocks. Embodied energy for one well is 400 x 25 = 10000. For 4 wells it is 10000 x 4 = 40000 MJ. Allocated over 100 years life and an area of 65 ha, the embodied energy is 6 MJ/ha/yr.

Pumps

The embodied energy for pumps is 160 MJ/kg. The weight of pump is assumed to be 40 kg. There was one pump on each block. The embodied energy in one pump is 160 x 40 = 6400. For 4 pumps it is 6400 x 4= 25600 MJ. Allocated over a life of 15 years and area of 65 ha, the embodied energy of pump is 26 MJ/ha/yr.

Pipe

The pipe is a combination of a mainline, sub-main and laterals (Saunders et al., 2006).

Mainline: the mainline is assumed to be 20 percent longer than the cropped orchard width which is 120 m/ha. The pipe is 65 mm PVC at a weight of 0.74 kg/m. The embodied energy coefficient of mainline is 120 MJ/kg. The total embodied energy is 10680 MJ/ha. Allocated over 40 year life, the embodied energy is 267 MJ/ha/yr.

Sub-main

Sub-main is the same width as the orchard and is 100 m/ha. The sub-main is 50mm PVC pipe at a weight of 0.51 kg/m. It comes to a 51 kg/ha. The embodied energy is 6120 MJ/ha. Allocated over 40 year life, the embodied energy is 153 MJ/ha/yr.

Lateral

The lateral pipe is 16mm semi-intensive polyethylene (LDPE). The length is equal to total row length which is 2500m/ha. At a weight of 0.07 kg/m and an embodied energy of 160 MJ/kg the total embodied energy is 28000 MJ/ha. Allocated over 30 year life, the embodied energy is 933 MJ/ha/yr.

The total embodied energy per ha per year is the summation of the above:

6+26+267+153+933= 1385 MJ/ha/yr.

Embodied energy in frost protection system – in kiwifruit and apple systems

The frost protection system is in the form of two bladed wind machine, the weight of which is estimated to be 1 tonne. The wind machine consumes 20 L of diesel/hr and covers an area of 5 ha. The embodied energy coefficient in the frost protection system is considered to be 160 MJ/kg, with a working life of 15 years following Wells (2001). Thus, the embodied energy in frost protection system comes to 2133 MJ/ha/yr.

GLOSSARY

First law of thermodynamics

First law of thermodynamics states that the energy-matter can neither be created nor destroyed, only altered in form.

Emergy

Emergy is the available energy that was used in the work of making a product and expressed in units of one type of energy - usually sunlight. Howard Odum, the ecologist, uses emergy analysis to assign standardized values to things of interest to society. His reference standard is one joule of sunlight.

Emergy analysis

Emergy analysis is a quantitative method of evaluating system based on the use of solar energy as a common denominator so that flows and storages of different types can be expressed and compared.

Energy analysis

Energy analysis is a quantitative method of evaluating system based on the use of energy usually expressed in the thermal equivalent of heat.

Life cycle analysis (LCA)

Life cycle analysis is a tool that provides a systematic way to consider the impact of a material or component over its full life – from extraction to processing/ manufacturing to construction/installation to use to eventual disposal.

Second law of thermodynamics

Second law of thermodynamics states that no conversion of energy from one form to another is complete; energy-matter is transformed from stable, highly usable (low-entropy) energy into disperse, less usable (high-entropy) energy.