Energy in New Zealand Apple Production

A thesis presented in partial fulfilment of the requirements of

Doctor of Philosophy

in

Science

At Massey University, Palmerston North, New Zealand

Thomas Gregory Frater

2010

ii

Abstract

Agriculture is the largest contributor to the New Zealand economy, and apple (Malus sp.) production is a significant component of that. Apples are exported from New Zealand to global markets, including Asia, the UK, Europe and North America. New Zealand prides itself on a 'clean green' image, and its agricultural industry, while already recognized as highly efficient, has sought to move towards sustainability. To further understand the sustainability of its production systems, the New Zealand apple industry sponsored a study to measure energy inputs into those systems.

Global food supply chains impinge on a broad range of issues, and have attracted academic commentary from a range of academic disciplines, ranging from the sciences and social sciences to the humanities. This inter-disciplinary study was structured as a scientific investigation of energy inputs into New Zealand farm level and post-harvest apple production (to destination port), with a parallel examination of the research process from a philosophical and systemic frame of reference. The author examined boundary judgments and presuppositions, drawing from the philosophical concept of tacit knowledge. The research process was structured so that outputs might contribute to further studies following the life cycle assessment (LCA) framework. Aspects of LCA methodology were therefore examined, particularly the construction of sustainability indicators.

The most significant contributions to the New Zealand apple production supply chain were found to be shipping (4.24 MJ kg^{-1}), packaging (1.46 MJ kg^{-1}), followed by farm processes (1.45 MJ kg^{-1}) and post harvest processes (0.51 MJ kg^{-1}). The total system inputs were 7.7 MJ kg^{-1}. The philosophical and systemic inquiry found that LCA methodology should take further account of normativistic elements to sustain the claim of being an holistic or systemic methodology. The meaning of sustainability indicators was found to be materially affected by tacit knowledge imbedded in apparently value-free metrics, and further affected by tacit assumptions imbedded in the LCA methodology itself. An approach (total life cycle intervention) was proposed, incorporating aspects of soft-systems thinking, taking account of critical system heuristics (CSH), and systemic intervention approaches.

II

Acknowledgements

I wish to thank Pipfruit New Zealand for their initial direction and sponsorship of this research, particularly Mike Butcher for his patient support. I am grateful for those apple growers who found time to reply to the farm level energy survey, and particularly for those who responded to further requests as the research progressed. I thank the two organisations, and the good folk within them who provided data for the post-harvest case studies. I thank you for your patience and generous support.

My supervisors deserve long-service awards as well as gratitude. John Mawson supported me through the early years of the research, providing practical direction and avenues of thought I would not have otherwise considered. Ralph Sims also offered early support, before absconding to Paris in the service of the planet, then returning in the latter stages to provide much needed constructive criticism. I thank Don Cleland for stepping into the breach, again in the latter stages; offering time that was already committed elsewhere. To Julian Heyes I offer special thanks, for providing criticism, motivation and support in the latter stages, and particularly for engaging positively in those areas for which I ventured outside the bounds of pure science.

I thank Don Houston for his friendship, and for guiding me towards systems thinking, and also my friends and colleagues at Massey. My GP and cardiologist also deserve a mention, for ensuring that my body remained attached to my soul, while my friends at St. Andrews CHB ensured that my soul remained connected to my body.

Thanks to Ian, Doug, Di, Dave, Trevor, David, Carl, Gareth, Blair, Dennis, Warren and Brian; to Dave, Morten and Hans; to Kim, Ian and Ross and to Ralph Hopcroft.

To Anne I offer the most gratitude, firstly for continuing to earn a living while I was distracted elsewhere, but more for your consistent love and companionship.

IV

Contents

X

List of Tables

Chapter One - Introduction

1.1 The problem

This study was initiated as a response to the emergence of the concept of 'food-miles'. The New Zealand apple (Malus sp.) production industry sought more information about the energy content of their production system. Industry representatives expressed concerns about previous studies that appeared to have been leveraged by competitors so as to disadvantage the New Zealand apple industry. Of particular concern were results that had been reported as numerical sustainability indicators. Such indicators were derived using peer-reviewed methodologies, and had been adopted by stakeholders outside of the scientific community as immutable fact, and yet were perceived by New Zealand stakeholders to unfairly represent their production system.

1.1.1 The proposal

A pure energy study was proposed by apple industry sponsors after the style of a dairy industry report (Wells, 2001). The initial proposal was expressed in terms of reporting benchmark energy indicators for New Zealand apple production.

1.2 The academic context

The Wells (2001) report was found to be typical of agricultural energy reports stemming from the energy crisis of the late 1970s. However, it became apparent as the apple energy study progressed that the field of energy usage in agriculture was increasingly being interpreted and applied in the emerging context of the field of global climate change. The issues of carbon emissions, global warming and anthropogenic climate change were consequently identified as the primary context of this thesis. These issues sit within the broad context of sustainability, encompassing aspects of environmental degradation and loss of bio-diversity, and encroaching on questions of an ethical, systemic and philosophical nature.

While an energy study following the style and methodology of Wells (2001) would have achieved the objectives of the New Zealand apple industry, it was adjudged that a comprehensive study of an entire industry should not be limited to the perspective of

a single stakeholder. Several other distinct stakeholder groups, including consumers, Northern and Southern Hemisphere competitors, environmental activists and sustainability researchers were identified, each with differing and sometimes conflicting perspectives. An implication of the conflicting views of stakeholders, underscored by the concerns expressed by the apple industry sponsors, was that factors exist that are imbedded deeply within accepted scientific methodologies, influencing both the meaning of results and their application to political and commercial activities.

1.2.1 An ethical dilemma, leading to a further avenue of research

The methods by which sustainability indicators have been derived by previous researchers (Sect. 2.4) suggested a more fundamental line of research stemming from the energy study. On one hand, energy research appeared to be a form of pure science that could be philosophically distanced from any commercial implications, but on the other hand, New Zealand stakeholders believed that the interpretation of those findings by popular media or political interest groups had impacted negatively on the commercial viability of New Zealand food exports. The scientific findings have since been significantly reinterpreted, but if the perception of New Zealand stakeholders is correct the market perception has been irrevocably influenced by the earlier reports[1].

This historical situation exposed a risk (and an ethical dilemma) that findings from my research might also be interpreted in a fashion that could harm (or benefit) individuals and communities with whom I was intimately connected. There appeared to be a lack of safeguards around frameworks of scientific research where the research context impacted on human activities such as global food supply systems. An alternative approach was to address this very issue: to further elucidate the interaction between science and human activity, and to search for a mechanism that might place further safeguards on research that might potentially influence commercial and political decision-making. An energy analysis was therefore the scientific framework on which this research was framed. However, the energy study provided a platform for an exploration of philosophical, ethical and systemic issues beyond the disciplines in which the study was conceived.

---

[1] See Sect. 2.3 for a discussion of the literature and issues surrounding the concept of "food-miles".

1.3 The philosophical, ethical and systemic component

To elucidate the connection between scientific study and global commercial enterprise, and to identify a mechanism that would offer a higher level of safety for researchers and stakeholders, I sought to understand or clarify:

- why researchers studying the same field, using similar methodologies could legitimately derive dissimilar or contradictory conclusions
- the nature of the methods used, and whether they might impose hidden constraints on the conclusions derived
- the nature of sustainability indicators, and whether apparently 'value free' numerical calculations might embody tacit value and boundary judgments
- methods that would assist scientists to surface the assumptions of their own work, material informing their work, and the work of peers
- an approach that would bring a greater level of integration between research and deliberate interventions resulting from that research, and reduce the likelihood of unintended consequences.

An area of concern in sustainability literature provided a direction for this section of the study. A situation was identified that appeared at least superficially to contradict the notion of scientific objectivity. A number of Northern Hemisphere studies (Anon, 1994, Blanke and Burdick, 2005, Gunther, 2002, Jones, 2002, Stadig, 2001) published in the late 1990s and early 21st century offered conclusions that fostered the development of a popular European environmental perspective that viewed local, seasonal food as the ideal case, Southern Hemisphere imports as the worst case[2], and transport distance as a key indicator. In comparison, a US study (Heller and Keoleian, 2000) provided a radically different set of indicators that treated environmental, social, economic and energy factors on equal terms. New Zealand researchers (Saunders *et al.*, 2006) responded defensively to the European studies, providing a countering perspective. However, despite more recent comprehensive and balanced European studies (Yakovleva *et al.*, 2004, Smith *et al.*, 2005) the popularisation of the term 'food miles' has been perceived by Southern Hemisphere food producers as achieving a pernicious undermining of their environmental credibility.

---

[2] Notwithstanding that Stadig (2001) found a mid-European case to be worse than New Zealand

Notwithstanding the suspicion that scientific studies were being used to support political agendas (Barber, 2004b), the potential negative economic consequences for the New Zealand apple industry were probably not anticipated by European researchers. This prompted the question of whether scientific methods used to study food production systems took adequate account of systemic ramifications. Differences in findings between various studies appeared to lie in the boundaries of the studies and the pre-suppositions of the scientists conducting them. This indicated a need to search widely for commentary on boundaries and pre-suppositions.

Food supply chains with their intrinsic dependence on energy (Fluck and Baird, 1980) and their ethical ramifications (FAO, 2006) are arguably unique in the extent to which they impinge on a range of global issues. In addition, the context of the field has evolved rapidly over three or four decades, from the environmental awakening of the mid to late 60s (Carson, 1963), through the energy crisis of the mid 70s (Pimentel and Hall, 1984) and a period in the early 80s in which the over-riding concerns were the ecological crisis and the dangers of nuclear energy (Rothman and Lichter, 1987) to the emerging awareness of global climate change (IPCC, 2007). I questioned whether the unique characteristics of food supply chains might reveal issues that are present, but obscured in other fields.

The study sought to explore the extent to which sustainability indicators in particular are 'value free'. It further sought to establish whether the methods by which sustainability issues are derived are themselves underpinned by normative value judgments.   It sought safer ways of building scientific knowledge in rapidly moving fields, or fields that have global systemic ramifications.

The methodological context of the research was closely aligned with the Life Cycle Assessment (LCA) methodology. Although agricultural energy research originally occupied distinct methodological niche (Fluck and Baird, 1980), it has come to be perceived as a component of LCA (Curran, 1993). Therefore LCA was identified as the broad methodological context for the philosophical and systemic enquiry.

1.4 The geographical and industrial context

An apple production industry is sited in the main islands of Aotearoa[3] New Zealand. The geological and geomorphological characteristics of Aotearoa result from its formation adjacent to a subduction zone between the Indian-Australian and Pacific tectonic plates. The landmass is long and narrow (approximately 1600 km long by 400 km at its widest point) lying on a S-SW to N-NE line (34° S to 47° S) 1600 km to the east of Australia in the roaring forties. The apple industry is sited in rain shadow zones on the east of both islands, and in a northern sector of the South Island[4] (McKenzie, 1987).   The New Zealand economy is dominated by the export of agricultural products (MoRST-SLURI, 2004), of which the apple industry is a small but significant contributor. In the 2003-2004 year (surveyed for the farm level report) the New Zealand apple industry exported 484 million NZD worth of apples, grown on 12150 ha (MAF, 2005).

1.5 The inter-disciplinary nature of the research

The subjects of pre-suppositions and boundary choices pointed to an examination of systems literature, indicating the need for an interdisciplinary exploration, including aspects of management and social sciences and the humanities in addition to the pure science core. These diverse disciplines were perceived to be linked by the common acknowledgement of the works of the philosophers of science, and widespread recognition of the systemic nature of the global context of sustainability.

1.6 Research objectives:

- To measure and report benchmark energy indicators for the New Zealand apple production supply chain

- To clarify the understanding of assumptions, boundary judgments and systemic issues in global food supply

- To provide an improved approach for managing interventions into global food supply systems.

---

[3] The Maori name Aotearoa is used here to identify the landmass of New Zealand as opposed to the wider political, social and economic environment (King, 2003)

[4] New Zealanders have traditionally referred to the two main islands as "*the* North Island" and "*the* South Island" rather than "North Island" or "South Island".

Chapter Two - Background and Literature Review

2.1 Introduction

This study was initiated as a response to the emergence of the concept of 'food-miles', awareness of which prompted the New Zealand apple production industry to seek more information about the energy content of their production system. The study was envisioned by apple industry sponsors as an energy study after the style of a New Zealand dairy industry report (Wells, 2001). The field of agricultural energy studies is supported by a body of knowledge, eminent contributors and seminal works. In a more recent environmental study of food supply systems (Mila` i Canals *et al.*, 2006), energy was treated as part of a broader life cycle analysis (LCA) methodology. Although my study was not intended to constitute a complete LCA of the New Zealand apple industry, components of the study could inform future LCA studies. LCA is the dominant methodological context of this study.

New Zealand's role as a supplier of food to global markets has attracted substantial academic attention (Blanke and Burdick, 2005, Jones, 2002, Stadig, 2001). The antipodean geographical position of New Zealand with respect to UK and European markets places it as one of their most distant traditional suppliers of produce. This has resulted in New Zealand agriculture becoming a focus of studies informing the subjects of global food supply chains, and their relationship to wider issues of sustainability.

The field of energy usage in agriculture was found to be increasingly interpreted and applied in the broader context of the emerging field of global climate change (Barber, 2004b, Barber, 2009). The issues of carbon emissions, global warming, and anthropogenic climate change were the global context of the research. These subjects sit within the broad academic field of sustainability, encompassing aspects of environmental degradation and loss of bio-diversity.

The original scope of the study failed to recognize the broad range of disciplines that have engaged with the issues of global food supply. The study was instigated as a scientific study; sited and supervised in an engineering and technology school. Nevertheless, a preliminary overview of the literature revealed that the field of food

supply chains has attracted direct attention from a broad range of disciplines, including economics (Arrous, 2000, Pimentel and Hall, 1984), sociology (Gunther, 2002), ethics (FAO, 2006, Rolston, 1996), geography (Grosvenor *et al.*, 1995), systems thinking (Giampietro, 2004, Giampietro *et al.*, 1994, Ison *et al.*, 1997) and policy (Pretty *et al.*, 2005). Within the sciences, commentary has been attracted from an equally broad range of disciplines including agronomy (Boxelaar *et al.*, 2003), climate change (Austin and Hall, 2001), veterinary science (Clark, 2002). In addition, government and international agencies (IPCC, 2007, Smith *et al.*, 2005) have contributed, plus the anticipated range of environmental, ecological, sustainability and technical disciplines. It was clear from the outset that whatever methodology was settled on, the study as a whole needed to be able to sustain examination and criticism from scientists, social scientists and even ethicists and philosophers.

2.1.1 Summary of subjects reviewed

The antecedent literature of agricultural energy investigations was reviewed, alongside the emergence of LCA as a widely adopted framework. The study was informed by literature emanating from a range of scientific fields that impinged on the main subject area, including organic production and composting, intensive horticulture and integrated pest management, alternative sources of energy and treatments of organic materials such as biofuels and bio-char. While energy was the primary focus, the subject of carbon emissions was a consistent background theme.

The issues surrounding global food supply chains are highly complex. The extent to which commentators outside of the sciences have engaged with food supply processes indicated that methodologies from other fields would provide a richer overall picture than the sciences alone could offer. The approach that emerged as potentially offering the most complete viewpoint was systems thinking, and the most significant learning offered in this study was supported by systems thinking literature. Both systems and scientific literature are built on, and informed by, philosophy. A review of systems literature was indicated, alongside philosophical commentary that linked systems thinking and science.

One specific study of relevance to my work (Simons and Mason, 2003) drew its methods from the industrial concept of 'lean thinking'. This approach appeared to offer important new tools and directions for energy studies, but the question of

whether the methods might have hidden presuppositions that would influence its findings required closer attention. The questions emanating from this examination became an important theme of this thesis. The subject of lean thinking, its history and its application were reviewed. Lean thinking evolved from within quality practice and science (Womack and Jones, 1996), and quality science exists within systems thinking (Beckford, 1998). All three were drawn from, and the relevant literature was reviewed.

The discipline of life cycle assessment (LCA) exists within life cycle thinking (a broad philosophical approach) and alongside life cycle management (a field of research and practice). LCA constituted the primary methodological context for the study. The methods adopted were considered to be part of the broad LCA methodology. The history and practice of LCA was therefore examined.

The specific context of this research was the New Zealand apple industry. Data gathering was undertaken mainly in that industry, both in apple production at the orchard level, and post-harvest operations including shipping. The refrigeration component of the research was supported by a study undertaken in the related kiwifruit industry. The New Zealand economy has historically been dependent on primary produce exports, of which the pipfruit sector is an important contributor. New Zealand apple producers have regarded themselves as highly efficient, producing high yields and competing successfully in international markets. The industry's success has reflected high levels of quality and service to global customers.

New Zealand apple production is supported by a wide range of horticultural research, much of which was not specifically relevant to the present study. However the subjects of organic production, integrated fruit production (IFP) and intensive production were explored as strategies for sustainability. The energy and sustainability context has been supported by similar research conducted in New Zealand agriculture. Research pertaining to my research, with the common characteristic of the New Zealand context, was reviewed. Other studies, with the common characteristics of energy, sustainability and apple production or food supply chains, were also reviewed.

2.2 Energy and the environment

The academic field of energy inputs in agriculture was established in the 1970s and has received continuing attention since that time. The energy content of agricultural crops including apples has been studied and reported by various authors both in New Zealand and worldwide (Fluck and Baird, 1980, Helsel, 1987, Pimentel, 1980, Pimentel and Hall, 1984). More recently, energy research has been reported in the context of sustainability (Barber, 2004a, Barber, 2009, Rizet *et al.*, 2008, Smith *et al.*, 2005, Venturi and Venturi, 2003), and indeed sustainability was recognised as the broad context of current agricultural energy research including the present study.

2.2.1 Sustainability

2.2.1.1 The Brundtland report

A seminal UN report (Brundtland, 1987), was commissioned to address concerns about (UN, 1987):

"the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development"

A particular concern of the commission was populations in developing countries most at risk from resource depletion. The report articulated the ethical concept of equality not only between people from different races and cultures but also between present and future generations. Sustainable development was defined as (p43):

"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

This definition has been widely cited, and can be regarded as consensual among both the academic and wider public communities. The terms of reference for the commission required it to address international co-operation, particularly between countries at varying stages of economic and social development. The report linked the issues of poverty and environmental degradation. In a keynote speech (Hauff, 2007) six issues were identified in the Brundtland report that remain relevant: conflict prevention, poverty, growth, energy and climate, food security and urban sprawl. Of

particular significance was the change in awareness of the energy / climate link. Hauff (2007) explained that the Brundtland report was highly criticised for comparing climate change to nuclear war, but that in 2007 this comparison was considered realistic. That change in awareness, and its ramifications, exemplified rapid changes in both context and collective tacit knowledge that are argued in Sect. 3.2.3 to impact on the meaning of sustainability indicators.

2.2.1.2 The UN Millennium Project

The UN Millennium Project report (Melnick *et al.*, 2005) represented a consensus of scientific opinion with respect to sustainability. The authors adopted the Brundtland definition of sustainability, but referred to "environmental sustainability" rather than the "sustainable development" of the Brundtland report. The terms of reference were defined within wider objectives to reduce global poverty, so the findings were weighted towards human survivability issues, particularly issues that contribute to third world poverty. The report summary included this statement (p2):

"The pursuit of environmental sustainability is an essential part of the global effort to reduce poverty because environmental degradation is inextricably and causally linked to problems of poverty, hunger, gender inequality, and health."

Nevertheless, the authors clearly specified the major global issues impinging on sustainability, and offered a plan to address these issues.

Five direct drivers of environmental deterioration were listed:
1. Land cover change
2. Over-appropriation or inappropriate exploitation of natural resources
3. Invasive alien species
4. Pollution
5. Climate change,

and six indirect drivers of environmental deterioration:
1. Demographic change
2. Economic factors
3. Market failures and distortions

4. Scientific and technological change

5. Institutional gaps

6. Socio-political factors.

To address these issues, the authors recommended an ecosystem-based approach that took into account the complex inter-relationships between human populations and ecosystems, and moves away from discrete sector analyses to a more holistic approach.

The New Zealand apple industry exists in a context in which many of the above issues are already being addressed at a policy or regulatory level. However, there are still specific issues within these listed drivers that impinge on the future of apple production in New Zealand. The following discussion considers the relevance of the five direct drivers of environmental deterioration listed in this report to the New Zealand apple industry.

Land cover change

New Zealand apple production practices represent an intensive form of food production. The historical progression from native vegetation to agricultural pasture (King, 2003) incurred much more significant environmental degradation than a change from agricultural pastureland to horticultural production. Nevertheless, the latter change was still a form of intensification that implied increases in resource use and pollution if not losses in biodiversity. Giampietro (2004) pointed out that the question that has invariably *not* been answered in industry studies was how much room exists in a system for further intensification. The question of whether intensive apple husbandry practices are more or less sustainable than conventional practices is addressed in Sect. 4.1.

Over-appropriation or inappropriate exploitation of natural resources

Current worldwide agricultural production systems are dependent on fossil fuel reserves. The use of these mineral resources impinges on aspects of natural resource depletion, pollution and global climate change. A link between mineral resources and natural resources is the increasing use of land and food crops for biofuel (Madsen, 2007). The questions here go far beyond any one nation or industry, and the

Millennium Group report (Melnick *et al.*, 2005) was more concerned with equitable distribution of resources than a commitment to reducing fossil fuel inputs. However, sustainable future solutions to energy dependency issues must avoid impacting negatively on natural resources (Engstrum *et al.*, 1990).

Water resources are recognised in the UN report (Melnick *et al.*, 2005) as a critical resource but the exploitation of mineral or groundwater resources has been managed in New Zealand at regional government level, so the apple industry is exempted from direct responsibility for these sustainability issues. Water resources do require energy inputs: specifically direct energy inputs required to extract and distribute water from aquifers or surface resources to the crop for irrigation or frost protection. While the exploitation of fossil fuel reserves is widely argued to be unsustainable, the sustainability of alternative technologies is subject at least to the criteria specified by Melnick *et al.* (2005).

Invasive alien species

At first inspection, the issues of bio-diversity loss and the spread of invasive alien species appear to be a step removed from energy issues. However this study proposes loss of bio-diversity as a common currency for measuring otherwise irreconcilable environmental costs. New Zealand has a commitment to a substantial conservation estate (McKenzie, 1987), despite pastoral and horticultural land in New Zealand being largely occupied by foreign species. The quality of this national investment can be used in arguments about the sustainability of the total New Zealand production system. Conversely, if any proposed solution to energy issues entails degradation of marginal land retaining significant indigenous bio-diversity, then that solution cannot be argued to be sustainable unless it is balanced with the rehabilitation of other degraded environments. It can be seen that losses or gains in indigenous bio-diversity can be used as a common currency in trade-offs between agricultural intensification and environmental rehabilitation.

Pollution of air, soil and water

Pollution can be considered to occur when the addition of a substance to an ecosystem impacts on a species' ability to survive. The level of pollution depends not only on the extent to which a species is impacted, but the importance we place on the species

(Melnick *et al.*, 2005). The authors of that UN report referred to pollutants mostly in terms of their direct or indirect impact on human populations, but other commentators have adopted broader frames of reference. The natural step (TNS) framework offered perhaps the most fundamental definitions (Robert *et al.*, 1997).

The exploitation of energy sources has a number of ramifications in terms of pollution. The combustion of fossil fuels is a primary source of greenhouse gas emissions as well as other toxic substances (Buhaug *et al.*, 2009). The apple industry is aware of emissions resulting directly from its production activities (Mila` i Canals, 2003), and has addressed those emissions through its integrated fruit production (IFP) protocols (Batchelor *et al.*, 1997).

2.2.2 Climate change

The phenomenon of global climate change has received enormous attention both in academic research and in worldwide media. The Intergovernmental Panel on Climate Change (IPCC, 2007) has sought to facilitate a consensus of academic opinion. The authors of that report considered climate change to be a crucial subset of the wider issues of sustainability. The present study acknowledges those findings as representing international scientific consensus, and generally does not consider viewpoints ranging outside of those expressed as uncertainties by the IPCC contributors. However, it is acknowledged that dissenting opinions exist within the scientific community as well as the more widely publicised popular media.

2.2.2.1 Brief summary of climate change research since 1990

In the early 1990s a number of publications drew the attention of the scientific community to the possibility of a positive feedback cycle induced in the relationship between rising global temperatures and rising atmospheric CO_2 levels. A model suggested a strong interaction of increased temperature and CO_2 concentration (Long, 1991), while an examination of respiration rates in an increased CO_2 environment, revealed complex responses among multiple factors, with uncertainty about the net direction of change (Amthor, 1991). A positive feedback mechanism from an increased rate of decomposition of soil organic matter in a warmer global climate was proposed (Jenkinson *et al.*, 1991), followed by a predicted net positive response from models of the soil / vegetation system (Smith and Shugart, 1993). A coupled ocean-

atmosphere model (Cubasch *et al.*, 1992) examined four IPCC scenarios over 100 years. This model predicted a 2.6 K rise for a "business as usual" scenario, and a 0.6 K rise for a stringent abatement scenario. This model appeared to confirm that not only were climate change responses real and significant, but that amelioration interventions were feasible. A revised model that included sulphate aerosols achieved a closer correlation with observed changes, predicting a 0.3 K per decade rise (Mitchell *et al.*, 1995).

In addition to these model-based predictions, a decadal warming trend in the North Pacific was reported (Hurrell and Trenberth, 1994). Although this report held back from linking the observations with global warming, a subsequent report based on Greenland ice-cores reporting a warming trend in the North Atlantic (Hurrell, 1995) appeared to provide more evidence of a global trend. Since this early work, the initial studies have been refined and their validity generally confirmed. New models and further research have strengthened the consensus that anthropogenic climate change is real, and that global mitigation strategies are imperative (IPCC, 2007).

The key conclusions of IPCC (2007) were:
- CO_2 is the most important anthropogenic greenhouse gas (GHG), and CO_2 levels exceed any historically[5] measured levels
- the primary source of increased atmospheric CO_2 is the combustion of fossil fuels, with land use change an important secondary cause
- atmospheric nitrous oxide concentration has increased significantly due primarily to agriculture
- the combined radiative forcing of anthropogenic GHGs is unprecedented in 10,000 yrs.

These authors described a range of other analyses and findings, detailing atmospheric, tropospheric and oceanic temperature changes, glacial snow melt, sea level rises and global climate trends, providing projections and outlining mitigation strategies.

---

[5] A study of 90,000 analyses since 1812 (Beck, 2007) provides a context for the term 'historical'.

A useful summary of the greenhouse effect and climate change (Wiegard, 2001) outlined the perspective of an Australian paperboard manufacturer (a supplier of apple packaging materials to Australasian markets). The author also provided a summary of political events, actions and responsibilities from 1979 to 2000 culminating in the progress (and lack of progress) surrounding the Kyoto protocols (Wiegard, 2001,).

2.2.2.2 Climate change and New Zealand agricultural production

A study deploying the CLIMPACTS model (Austin and Hall, 2001) predicted the effects of climate change on the production of apples in New Zealand. The authors limited their study to the immediate effects of predicted global climate changes on apple growth. They discussed the ramifications of three IPCC climate change scenarios (SRES A2, SRES A1, and SRES B1), and considered the ramifications of more frequent El Niño events, and overall warmer winters, with corresponding disruption to winter chill patterns.

Predicted effects of climatic trends to New Zealand were reported as:
-   increased likelihood of extreme weather events (El Niño seasons, floods)
-   increased likelihood of droughts in eastern districts
-   increased rainfall in western districts
-   warmer mean temperatures.

New Zealand is likely to experience a smaller temperature increase than global means. However sea level changes may lead to salt water intrusion into aquifers, and inundation of important cropping land. They concluded (p 52):

"the results suggest producers are unlikely to observe a consistent and pronounced change in fruit development over the next 25 years, even under the IPCC SRES A2, high climate sensitivity scenario. This is because predicted changes in dates and potential size are small relative to present year-to-year variability." and,
:
"We conclude that the New Zealand apple industry is unlikely to observe major changes in apple production due to global warming. Changes are more likely to be driven by marketing requirements than by the impacts of predicted climatic changes."

The authors did not elaborate on these "marketing requirements", however they did acknowledge that climate change issues might indirectly influence the market. Austin and Hall (2001) offered an optimistic outlook for the future of apple production in New Zealand. However they did not attempt to predict the systemic effect of indirect changes, including extreme events and political and market forces.

2.2.2.3 The relevance of climate change to the present research

The relevance of climate change research to this study is not so much the predicted impact on New Zealand, but its importance as the global context for energy research. Climate change is of pressing concern to national and international policy makers, and the subject at hand (energy use in food production) is of direct relevance to the issues represented in this debate. The placement of this debate in the wider context of sustainability (IPCC, 2007) linked the survival of human populations, particularly marginally sustainable third world societies (FAO, 2006, Melnick *et al.*, 2005) with the use of resources, first world affluence and global trade.

The complexity and interrelatedness of these issues was seen as the primary indicator of the potential usefulness of systems methodologies for sustainability research in food production.

2.2.2.4 Evolution of public perception

Researchers operate within a frame of reference that is shaped partly by scientific knowledge and partly by global awareness and concern over a range of issues. An examination of public attitudes to nuclear energy (Rothman and Lichter, 1987) argued that disparate views between scientists and public were at least in part a symbolic or surrogate critique of liberal capitalism. The contribution of these authors is argued here to inform the climate change debate, by demonstrating the complex mechanisms that can underlie public attitudes toward scientific knowledge. These authors also described the evolution of public attitudes toward nuclear energy and a range of other issues relevant to sustainability debates prior to 1987. Hannigan (2006) provided an historical, sociological perspective of the development of environmentalism, including the evolution of debates around climate change and global warming. The author's arguments are framed within, but not limited to a social constructionist viewpoint. He reviewed the role of scientific, political and media actors in the emergence of global perspectives and debates.

2.3 Food transport

2.3.1 Food miles

Early European sustainability research identified advantages in producing food products as close as possible to the market (Gunther, 2002). A related sociological debate supported the concept of embeddedness as a counter to globalisation (Winter, 2003). These notions and the emerging concept of food-miles contained an implied criticism, and consequently a threat to New Zealand as a Southern Hemisphere food exporter. New Zealand growers might argue that their production methods are efficient, and that they are moving towards the goal of sustainability.

2.3.1.1 Early history of the food miles debate

An early appearance of the term 'food miles' (Saunders *et al.*, 2006) occurred in a report published by the UK organisation SAFE Alliance (Anon, 1994). Since then the term has achieved both academic and popular usage.

A study of UK food systems (Pretty *et al.*, 2005) broadened the boundaries of inputs into UK food production to include road transport from farm to shop, and shop to home. The authors claimed to measure the 'full costs' of food production, by calculating the costs arising at various stages through the food production system. These authors recognised a range of externalities including both external costs incurred in the production of the food, and external benefits that they did not attempt to measure. They used the term 'food-miles' in their title, reinforcing their conclusion that food produced closer to the point of consumption incurred lower costs than food produced at greater distances. It is significant the contribution of sea transport was reported to be only 0.65% of the costs of transporting food on UK roads, however this was due to low volumes rather than low impact in proportion to volume. New Zealand was identified as the most distant supplier, and by implication the 'worst case'. A major conclusion of these authors related to production systems rather than transport, advising significant benefits if the UK was to adopt organic farming on a widespread basis.

From the perspective of the New Zealand apple industry, one important concession that Pretty *et al.* (2005) made is that a theoretical case exists for transferring

production to overseas suppliers. Generally, they argued that this transference would not reduce global environmental costs, but that it would reduce local costs. They then added (p8):

"If overseas production systems were more environmentally-beneficial in comparison with domestic ones, then there may a net environmental benefit (after transport costs were also accounted for)."

Pretty *et al.* (2005) also provided a concise summary of the recent history and literature surrounding the issues of food production systems, food transport and environmental models in the context of sustainability.

Smith *et al.* (2005) analysed the validity of food-miles as a sustainability indicator[6]. They reported that the concept of food-miles had come to represent a broader range of global issues than simply the transport of food and its direct impacts. They explained that the term was aligned with a range of social and economic issues, including the wider debate around globalisation. The authors summarised the costs associated with food transport. They reported that urban transport incurred the greatest accident and congestion costs. Urban transport was also responsible for the greatest air pollution impacts, as distinct from air pollution costs where heavy goods vehicles (HGV) were the main contributors.   HGV transport also incurred the greatest noise and infrastructure cost.   Air transport incurred the greatest environmental impact, and incurred the greatest cost per volume. Shipping was reported to be relatively efficient. The main findings reported were:

-    a single indicator based on total food kilometres was an inadequate indicator of sustainability

-    data were available to provide and update a meaningful set of indicators on an annual basis

-    food transport had significant and growing impacts

-    the direct environmental, social and economic costs of food transport were over £9 billion each year, and were dominated by congestion.

---

[6] A comprehensive report to DEFRA

The key indicators proposed were:

- urban food kilometres

- heavy goods vehicle (HGV) food kilometres

- air food kilometres

- total CO_2 emissions.

In summary, Smith *et al.* (2005) supported the point of view of Saunders *et al.*, (2006) reviewed below, that the total kilometres travelled by food was an inadequate indicator of environmental impact and sustainability. The indicators they recommended demonstrate that transport generally incurs environmental and social costs, but that transport mode is more significant than distance per se.

2.3.1.2 New Zealand apples, food miles and the European perspective

The year-round customer demand in Europe for seasonal products has been satisfied by two basic competing supply chain strategies:

- the storage of local product for long periods

- transportation of product from the Southern Hemisphere

A Swedish LCA study (Stadig, 2001) consisted of a comparison of three different systems used to deliver apples to Sweden. Stadig (2001) compared a domestic system (Sweden), a mid-European system (France) and an 'overseas' system (New Zealand). That author focused on New Zealand's distance from its markets as a primary differentiating factor. The study compared the energy use of the three systems, and the environmental impact of pesticides used in production. The results placed New Zealand higher than the other two systems in energy use, and between France and Sweden (France being higher) in the environmental impact of pesticides.

Stadig (2001) concluded that Sweden's importation of apples from New Zealand was less sustainable than production systems geographically closer to the point of sale. The assumptions of this author represented those that were challenged (see following) by Saunders *et al.* (2006). The reason given for New Zealand being higher than the other two in terms of energy was the distance from its markets, and although New Zealand's use of sea transport was regarded as being relatively efficient, the large distances involved resulted in a significantly higher overall energy usage. Stadig

(2001) also suggested strategies for the reduction of environmental impacts and energy usage.

A UK study (Jones, 2002) provided a global value for the transport of food to the UK of one litre of fuel per 52 tkm. The author also provided a value (145×10^6 GJ) as the total energy expended in supplying food in the UK. He argued that there is a direct relationship between the source of a food product and energy consumption, and that transportation should be avoided where the same products could be cultivated locally with low external inputs. However, he also emphasized the efficiency of sea freight in comparison to land and air alternatives. He wrote (Jones, 2002) p574:

"Therefore, the six transport stages involved in the distribution of 1 kg of apples from New Zealand to a consumer in Denbigh … consume the same amount of energy as is required to boil a kettle full of water 53 times or run a 100-W light bulb for 50 hours."

These authors represented the consensus of thinking in Europe at least. The overall conclusion was that the distance between the point of production of an agricultural product and the end consumer was an indicator of the total energy inputs into supplying that product.

A study of primary energy usage for apples compared locally grown (Meckenheim, Germany) fruit with imported New Zealand fruit (Blanke and Burdick, 2005). Their finding of New Zealand fruit requiring a 27% greater primary energy input than locally stored fruit provided a significant downward revision of previous estimates.

2.3.1.3 Food-miles - a New Zealand perspective

An implication of Jones (2002) was that New Zealand represented the worst case as it was geographically furthest from Europe of any major supplier. The author claimed to provide a more complete picture than previous studies.   Any claim to completeness or holism with respect to a system should be made with due acknowledgement of boundary choices (Checkland, 1999). That is, there is no such thing as a complete model as the act of constructing a boundary implies that there are forces outside that boundary (in the system environment) that could be included in a larger more

comprehensive model. A New Zealand perspective was that many influences to the system were excluded from the early food-miles studies.

One issue that Jones (2002) hinted at, but did not explicitly measure, was the relationship between refrigeration and transport energy usage. Refrigeration (including controlled atmosphere storage) requires energy whether the product is being transported or not. Therefore a time dependent relationship in energy usage exists between production and consumption that is independent of distance. There is little argument that fruit produced efficiently in the immediate vicinity of the point of sale, and eaten 'in season', incurs the lowest overall costs. Energy costs in refrigeration, storage and transport are incurred 'outward' from that point in both time and geographical distance.

The general argument made by New Zealand suppliers is that because marine transport is relatively efficient, fruit in transit from New Zealand is comparable to fruit stored on land in Europe. In fact, since fruit from New Zealand can be delivered to selected ports, the higher land-based transport costs can be minimized. Jones (2002) did explicitly argue that the consumer demand for year round fruit supply was a driver of energy use.

Saunders *et al.* (2006) addressed the subject of food-miles in New Zealand agriculture. The authors examined the environmental impact of representative key agricultural export products from New Zealand, using an LCA approach. They argued that production systems within food supply chains have been represented as being equal, leaving Southern Hemisphere producers to appear disadvantaged as distance would be the significant difference between the different systems. The authors challenged that assumption, providing evidence that New Zealand production systems were highly efficient, and arguing that New Zealand food supply systems were competitive on an energy basis with European food supply systems. With respect to apples, Saunders *et al.* (2006) reported that the energy costs and CO_2 emissions incurred in delivering fruit to the UK (including transport) were 60% of the UK system.

In addition to the findings of that report, which relate directly to the context of my research, Saunders *et al.* (2006) provided a review of the history and issues surrounding the food-miles debate. They noted the arguments proffered by Barbour (2004) that the food-miles concept may be used for political rather than environmental purposes, as a trade barrier to Southern Hemisphere states seeking to export foodstuffs to Northern Hemisphere markets.

An LCA analysis (Mila` i Canals *et al.*, 2007) published energy data for apple production with respect to the concept of food miles. They compared four scenarios:
-   European apples consumed in the country of production,
-   apples produced in a European country different to the one in which they are consumed,
-   apples produced in New Zealand and consumed in Europe, and
-   apples produced by other Southern Hemisphere countries, including traditional and emerging suppliers of apples for the Northern Hemisphere.

Each scenario was assessed for four different seasonal periods. They confirmed that shipping is a major energy input for Southern Hemisphere fruit supplied to European markets. In the January and October scenarios, a clear advantage was reported for locally produced apples (locally grown produce, eaten in season). In both these months New Zealand fruit exhibited higher primary energy consumption than the other scenarios. However, in the April and August cases, there was more overlap, with land transport within Europe penalising that mode of transport. For the European spring and summer scenarios, no single reliable preferred supplier (from an energy usage point of view) could be identified, due to variability in production management practices, storage losses and land transport distances. The terminal boundary of the supply chain was the supermarket shelf, a boundary decision that has since been implicitly challenged (Browne *et al.*, 2008, Rizet *et al.*, 2008).

However, this analysis was valuable because it considered energy use of transport alongside the energy costs of storage. By reporting the impacts of consumption relative to the European seasons, it provided a clear indication of the periods for which New Zealand sourced apples would be competitive in energy usage terms.

2.3.1.4 The significance of domestic transport

An important contribution[7] to the food transport debate (Browne *et al.*, 2008) and (Rizet *et al.*, 2008), compared New Zealand, France and UK sourced apples for supply in UK and Europe. The energy cost of the domestic shopping journey was reported to be a significant energy cost. This did not affect the relativity of the various scenarios, but could be argued to have affected the significance of the differences. Their approaches used grams of oil equivalent (goe) as a common energy value between various transport modes. A key finding clarified questions raised by Blanke and Burdick (2005): the finding was not so much the expected high contribution of sea freight in the New Zealand cases, but the high contribution of consumer trip emissions between the supermarket and home, resulting in comparisons that showed less difference between the New Zealand and UK cases than previous studies.

2.3.1.5 Food miles summary

In summary, the debate around food-miles appears to have reached a logical consensus (among the scientific community at least). The transport of food does incur significant environmental and social costs, but these costs must be measured in conjunction with other costs incurred in the production and delivery of goods. The consistent finding that significant environmental impacts occur in the final stages of delivery does not exempt food suppliers from the need to systematically reduce energy usage and improve environmental outcomes in the earlier stages of the process and delivery chain. However, it has undermined the argument that total distance from farm to consumer is a fair indicator of sustainability. With respect to the present study, the food-miles debate was the catalyst for this investigation, but as the debate itself has moved on, so has the study. Unfortunately the term 'food-miles' has achieved a level of popular usage, and no matter what consensus is reached among scientists, the term will in all likelihood continue to be used for political or commercial purposes, or to espouse arguments that are weak or fallacious.

---

[7] These authors separately interpreted a single LCA study.

2.3.2 Shipping energy

Early agricultural energy studies (Boustead and Hancock, 1981, Pimentel, 1980) provided general transport energy values (such as 0.105 MJ t^{-1} km^{-1} for shipping freight). A more recent Australian parliamentary advice report (Webb, 2004) contained revised values for bulk shipping of 0.2 MJ t^{-1} km^{-1}, 0.4 MJ t^{-1} km^{-1} for rail and 1.4 MJ t^{-1} km^{-1} for heavy goods vehicle (HGV) road transport. Webb (2004) cited a draft report (Apelbaum, 2003) that contained more specific shipping energy consumption (0.23 MJ t^{-1} km^{-1}). (Corbett and Koehler, 2003) reported a fleet average fuel consumption rate of 206 g kWh^{-1} for transport ships, and a total of 2662 container ships in the world fleet with a total installed power of 43,764 MW. Jones (2002, p570) citing (Carlsson, 1997) reported the energy consumption of refrigerated products to be 0.035 MJ t^{-1} km^{-1} (by ship) and from 0.16 to 0.46 MJ t^{-1} km^{-1} (by road).

Corbett and Koehler (2003) provided global estimates for shipping fuel usage and emissions using a bottom-up methodology, deriving estimates from vessel specifications and reported activity. Wild (2008) described the technology and processes associated with containerised shipping. With respect to CO_2 emissions, a figure of 0.0063 kg CO_2 t^{-1} km^{-1} was provided by Smith *et al.* (2005) for bulk deep-sea food transport. This value was an estimate that included both dry bulk, and non-dry containerised foodstuffs.

Attention has been given to technological process improvement (Chao *et al.*, 1995) and fuel optimisation (Han and Gan, 2003, Hellstrom, 2003). A further study (Lancester, 2000) explored environmental sustainability criteria for shipping with respect to incorporating these criteria at the design stage. Sustainability issues between transportation modes, including technological, as well as regulatory and market-based solutions have been addressed (Bazari and Reynolds, 2005).

Shipping emissions have been the subject of a substantial body of research. Recent marine emission studies focused on sulphur and particulate emissions, using energy consumption as a data source rather than the object of the research (Delft, 2006, Buhaug *et al.*, 2009). Two basic strategies were reported:

-    A top-down analysis based on gross fuel usage from fuel bunkers, allocated to national and international fleets, and

-    a bottom-up analysis generated from the predicted performance of marine engines of known types.

Corbett and Koehler (2003) addressed a reported gap between the resulting calculations from the two strategies, offering an improved bottom-up methodology for predicting shipping fuel consumption and emissions.

An analysis of fuel consumption and emissions for ocean going vessels revealed a number of variables and uncertainties that impinge on energy usage, the primary concern of my study (EPA, 2000). The authors provided algorithms for fuel consumption and emissions derived from regressions of data sourced from 9 reports. The variables reported included fuel and combustion characteristics, engine speed and load. Container ships were reported as operating in the speed range of 20 to 22 knots, however the trend toward larger, faster ships indicated that containership speed was approaching 24 kts. They reported the introduction of at least 16 refrigerated container ships exceeding 4000 TEU[8] to global routes. The world average was closer to 2000 TEU (Kutz, 2004) a value that was influenced by smaller coastal vessels. Larger vessels that are more efficient because of their design, payload and speed, are preferred, but are not necessarily available for longer routes such as the NZ-Europe route. Further variables reported included payload (most reported data assumed maximum loading) and number of port calls per route (time spent in less efficient operating modes).

EPA (2000) reported an inverse exponential distribution for all emissions against fractional engine load. That is, large marine engines were found to be cleaner and more efficient when operated close to their rated loading. Four operating modes were described (full, half, slow and moored). These modes (for container ships) were related to main engine loads as 80%, 10%, 10% and 0% of the maximum power. This implied that time spent manoeuvring close to ports, or in high traffic areas, resulted in

---

[8] Twenty foot equivalent container capacity.

an additional energy and emissions burden. The authors stated that the efficiency of auxiliary engines followed the same pattern.

EPA (2000) reported a single value of 750 kw for auxiliary power for any vessel, rising to 1250 kW during manoeuvring, and 1000 kW during hoteling. These values didn't explicitly account for the energy demands of refrigeration. An uncertainty (discussed in Sect. 3.2.2) is whether refrigeration plant was driven by auxiliary power or by the main engines for specific vessel designs.

My calculations were based on EPA (2000). Nonetheless, it is acknowledged that an IMO report (Buhaug *et al.*, 2009) provided a significant revision of the EPA (2000) methodology, specifically modifying the 'bottom-up' process method to provide more reliable energy use estimates. Buhaug *et al* (2009) provided a wide-ranging report of international shipping, estimating that reported emissions based on previously accepted methods could result in under-reporting to the extent of 30%. The estimates of GHG emissions from refrigerated containers were of particular relevance to the apple production industry.

2.3.3 Refrigeration and refrigerated transport

(Merts and Cleland, 2004) reported energy usage in cold store refrigeration in New Zealand, providing benchmarks for New Zealand industry. The report was based on a survey of New Zealand cold store facilities. The gross storage volumes ranged from 9600 to 93000 m^3, with a mean of 34000 m^3. Specific electricity consumption ranged from 35 to 151 kWh m^{-3} (mean 79 kWh m^{-3}). The report detailed factors affecting energy usage, providing benchmark parameters such as throughput.

A Canadian study addressed energy saving opportunities in fresh fruit and vegetable processing and cold storage facilities (Hackett *et al.*, 2005). One significant aspect that the authors reported (p3) was that the hydro-cooling of fruit to remove field heat was superior to the use of evaporators. They provided details of energy and cost saving opportunities for both large scale and small-scale plants.

Methodological issues arising from the storage of a range of products in a single refrigerated space have been reported (East *et al.*, 2009). The authors assessed

different approaches to allocating emissions, preferring a heat load and refrigeration effectiveness basis to either mass or storage time. Where berryfruit, fish and apples were stored in separate rooms in the same facility, fish and apples were reported to be significantly disadvantaged where allocation was performed on a mass basis. In my study, where this issue was encountered it was reported as an uncertainty.

Practical and design-focussed solutions for reducing energy usage in coolstores have been reported (Thompson, 2001). A Victorian report (SEAV, 2002) typified energy-economics studies, reporting both pure energy and cost data, and recommendations that while relevant, were generally more applicable to a business context than a pure energy context.

2.3.3.1 Refrigerated containers

The energy requirements for refrigerated containers (Wild, 2008) have been reported to vary according to:

- running mode (low temperature mode is below -10° C, chilled mode above -10° C
- ambient temperature
- compressor type
- refrigerant gas

Wild (2008) reported draw-down loads of approximately 9.1 kW to 10.5 kW. The author recommended a broad average value of 3.6 kW / TEU. New Zealand apples are transported in chilled mode (requiring less energy than low temperature mode), and through both temperate and tropical regions, so this value was accepted as applicable to the context of my study.

The case study apple exporters reported that container ships have generally displaced refrigerated hold vessels for New Zealand apple freight. Wild (2008) further reported that integral refrigerated containers were displacing porthole containers. EPA (2000) reported the range of container ships in their survey to be from 20,000 ton to 70,000 ton.

2.4 Agricultural energy research

Early contributors provided an overview of energy use in agriculture (Fluck and Baird, 1980). An important aspect of work of these authors was a standardised approach for the measurement of agricultural energy interactions.

In considering suitable methodologies for the present research, their description of statistical analysis, input-output analysis and process analysis provided a useful starting point. Their description of statistical analysis was that of an overview in which the term 'statistics' was used in the sense of published national data rather than the sense of a mathematical discipline. Their work included descriptions of a variety of agricultural energy studies that have used the process analysis methodology. These authors claimed that input-output analysis was best suited to more complex systems such as national or regional industries, whereas process analysis is better suited to situations where the flow of goods and services is traceable. They offered a generalised procedure for process energy analysis (p60):

- decide objective of analysis
- choose a system boundary
- identify all inputs
- assign energy requirements to all inputs
- identify all outputs
- establish criteria for partition (e.g. where energy inputs need to be attributed to multiple products).

The authors also distinguished between gross energy and net energy requirements. They defined energy indicators (pp 183-185) including:

- energy productivity – the quantity of product produced per unit of input energy,
- energy efficiency (or energy ratio) - the quotient of energy value of the outputs and inputs, and
- energy intensity – the sequestered energy per unit of output

It is noted that other authors cited in my study have not universally adhered to their definitions. The term energy intensity for example is frequently adopted as a measure of energy use per unit area. Fluck and Baird (1984) did not claim originality with

respect to these concepts, but they did provide an important review of energy research in its early stages, and provided guidelines for ensuing research.

Pimentel (1980) provided a seminal publication in agricultural energy. This author was one of the researchers who realised that the energy crises of the early 1970s had implications for global food production. His research set about quantifying the energy content of agricultural systems, and exploring the ramifications of a future in which energy was less abundant. Pimentel (1980) is widely cited in agricultural energy studies, however his works extend well beyond this functional resource handbook to complex investigations into areas such as human energy and energy systems (Giampietro *et al.*, 1994). Pimentel and Hall (1984) for example, provided basic strategies for reducing energy inputs in agricultural production. Areas relevant to my study included irrigation, packaging and transport energy costs. Despite more recent revisions of indirect energy calculations (Audsley *et al.*, 1997), the methodology of Pimentel (1980) was found to be useful for estimating a wide variety of indirect energy values in both farm and post-harvest plant and machinery. Cowell (1998) has been credited (Mila` i Canals, 2003) with developing methodologies for adapting LCA to agricultural production systems.

A study of agricultural sustainability in Lithuania (Riesinger, 1999) reported the use of an energy balance method. The energy balance method considered the farm to be a 'black box', so that the inputs and outputs were considered rather than the internal energy exchanges. Riesinger (1999) argued that although energy losses occurred in practices such as manure storage and application, they could be omitted from the balance, along with the consumption of farm goods by workers (in a rural subsistence situation). This method was consistent with the orchard-based section of my study. Similar methods were adopted in the post-harvest supply chain, but were found to generate ambiguities (Sect 4.2.9).

The field of packaging energy is supported by a body of literature (Boustead and Hancock, 1981, Gaines, 1981, Selke, 1999), and questions emanating from it constitute an important theme of this thesis, explored further in Sect. 4.5. A study that measured GHG emissions from an Australian paper packaging manufacturing company (Wiegard, 2001) discussed strategies for GHG reduction in relation to the

(then unratified by Australia) Kyoto protocols. The author identified fossil fuel derived energy sources as a major component of emissions, plus solid waste disposal. She compared the use of recycled versus new materials as feedstock, considering opportunities for carbon sequestration. This author provided limited energy data for packaging, but did clearly demonstrate the extent to which emissions attributable to packaging vary by case and through assumptions and boundary decisions.

2.4.1 New Zealand agricultural energy research

An early body of work (McChesney, 1980, Sims and Henderson, 1984, Sims *et al.*, 1988, Smith, 1979) was conducted in the field of agricultural energy in New Zealand pastoral farming. The subject was extended further to political considerations (McChesney, 1991b), and to global issues (McChesney, 1991a). This body of work provided useful energy data in a New Zealand agricultural context.

A case study of energy and carbon indicators in New Zealand farms (Barber, 2004a) provided revised reference data that took account of developments in agrichemical formulation and usage in the New Zealand context. An overview of energy use in the New Zealand Dairy industry (Barber and Pellow, 2005) in the context of wider New Zealand agriculture provided comparative annual sector totals for energy usage to the farm gate (for sheep and beef 5.86 PJ, dairy 3.3 PJ, vegetable – protected 2.5 PJ, arable 0.99 PJ, vegetable – outdoor 0.56 PJ, flower – protected 0.44 PJ, pipfruit 0.24 PJ, kiwifruit 0.18 PJ and grapes 0.17 PJ.) The authors measured post-harvest energy costs to the shed or factory, offering a value of 0.023 PJ for pipfruit, assuming an average distance of 15 km to the packhouse. They offered a value for kiwifruit grading and cool-storage (0.697 kWh tray^{-1})[9].

A New Zealand dairy industry case study (Wells, 2001) was commissioned to support the MAF goal of maintaining and monitoring an information base on key indicators of sustainable agriculture and forestry. The report was significant to my research as it was identified early in the research planning process as a potential methodological model.

---

[9] These data were not directly comparable to the intensity values reported in Ch.4, but nevertheless constitute important reference values for New Zealand agricultural production.

Wells (2001) collected data for direct and indirect energy inputs from a total of 150 farms, representing 1% of national suppliers. Although the author made use of process-based measurements from earlier studies, he measured both inputs and outputs by directly surveying the usage on each farm. The objective of the report was stated as (p1):

"to determine baseline data on total energy inputs, as indicators of the sustainability of the dairy farm production sector."

The author continued, claiming these indicators to be valuable (for New Zealand):

" as tools for farmers and policy advisors to assess the overall sustainability of agricultural activities…to ensure the continued competitiveness of our food and fibre products…to provide policy-makers and planners with measures with which to assess the best use of land in the future."

A key finding was that energy use indicators varied widely between farms. Nevertheless the author offered metrics representing a 'national average' dairy farm, reporting a primary energy input (energy intensity) of 18 GJ per effective milking hectare per annum, and energy inputs of 22 MJ per kilogram of milk solids. He provided values for carbon dioxide emissions (excluding animal emissions) of 1.1 tonnes of CO_2 per effective milking ha, or 1.4 kilograms of CO_2 per kilogram of milk solids. Wells also identified the proportion of renewable energy within the total energy requirement.

The last point in the passage quoted above supports the argument (developed and challenged in Sect. 4.3, 4.4) that LCA practitioners assume that their task is to provide information for political decision makers, and that their work is isolated from future intervention into those systems.

Wells (2001) used his findings to compare the efficiency of New Zealand dairy production with its international competitors. He also described the variation within New Zealand, showing distinct differences between geographical regions. The dairy farming case study provided robust data for energy indicators in the New Zealand

agricultural context. Although he did not adopt LCA terminology, his methodology is compatible with broad LCA methodology. A full LCA study would consider a wider range of both inputs and emissions. For example, Wells (2001) provided data for carbon emissions without including animal emissions. Animal emissions have been recognised as New Zealand's largest single contributor to greenhouse gases (Clark, 2002). This subsequent emphasis did not compromise Wells' findings, however the boundaries of the Wells study are narrower than recommended for LCA (Guinée *et al.*, 2002). The restricted focus of the Wells study allowed the author to engage with a large sample group. That is exemplified by comparing his sample size (n=150) with the sample size (n=3, plus two sets of average data) for an orchard LCA case study (Mila` i Canals, 2003).

The climate of thinking in the area of agricultural sustainability has evolved since the Wells (2001) report, with concerns over global warming and climate change driving the research paradigm towards more holistic methodologies. While the Wells (2001) study is acknowledged as a methodological precedent, if that study were repeated the evolution of the global academic and social environment would demand a revision of the boundaries of the study.

2.4.2 Exergy and energy

Various treatments of energy indicators, particularly those involving biomass, include recoverable energy as a component of an indicator (Boustead and Hancock, 1981, Gaines, 1981, Selke, 1999). The term "exergy" refers to that component of a system that is available to be used by being converted to work. Exergy is environment dependent rather than an absolute thermodynamic property, however including calorific energy content in an indicator presupposes that the energy can be usefully recovered. In this study, where the inclusion of calorific energy content in indicators was examined, the term exergy was preferred.

2.5 New Zealand apple production

An ongoing discussion and body of literature has examined the political structure of the New Zealand apple industry (McKenna *et al.*, 2001, McKenna *et al.*, 1998, McKenna *et al.*, 1999). These authors have provided a useful general description of the New Zealand apple industry detailing its geographical context and political

history. Wide-ranging discussions focus on the transition from the pre-1996 single desk marketing structure to the present de-regulated structure, and the evolution of the IFP production protocols.

2.5.1 Organic production

Organic production has received increasing attention as a viable mode of fruit production. Organic production is typically represented as providing benefits to the consumer in terms of food quality, and to the environment in terms of sustainability. The farm level study (Sect. 4.1) examined organic orchards as a subset of the national orchard sample group.

An overview of organic farming as a strategy for sustainable global food supply (Rigby and Bown, 2007) described the move toward "industrial organic", or the capture of the organic movement by corporate business. The authors identified an assumption that equates organic farming with local, family-run mixed farms. They argued that this assumption was "unravelling" as new models of organic farming emerged.

Rigby and Bown (2007) held that organic farming has historically been equated with sustainable farming. In an earlier discussion paper (Rigby and Bown, 2003) they argued that this link is strongly supported in literature and industry (p15):

"On one side are those who see organic as a movement with social and environmental principles at its heart, whereas others regard it as a production standard, nothing more."

The authors explored the pressures that market preference and profitability were forcing on organic values, and examined the concept of food-miles as an analytical tool. A consistent theme was that shorter distances from farm to consumer made food production more visible, and by implication safer and better. However the authors did not provide evidence to support this assumption, but rather reinforced it as part of an historical set of values surrounding organic production. The authors did recognise the challenge that Saunders *et al.* (2006) made that conventional New Zealand production

systems were significantly more efficient in terms of energy and emissions than UK systems. They generally conceded that food-miles were only part of a bigger picture.

While the assumption connecting organic production with local, family-based, mixed farm production emanated from the UK context, the evolving organic fruit production systems in New Zealand (supplying export markets) exemplifies the trend toward a rationalisation of organic values and production systems. However, the anecdotal experience of my study suggested that the commitment and involvement of farmers (in New Zealand horticulture) espousing values associated with traditional 'alternative' movements demonstrates that organic production in New Zealand has not been captured by corporate industry to the extent described by Rigby and Bown (2007). Rather it could be argued that a compromise acceptable to both sectors has been achieved.

A dichotomy between organic and conventional production has been explored (Elliot and Mumford, 2002) in the context of a previous comparison of apples produced by three different production systems in Washington State (Reganold *et al.*, 2001). Elliot and Mumford (2002) argued that both organic and conventional systems impact the environment, but that organic production is driven by (p1):

"ideological principles rather than a pragmatic assessment of the environmental costs and benefits of farming practices".

They argued that the development of organic standards reinforced the dichotomy between the two regimes, where an integrated regime would achieve greater environmental benefits overall. Their reasoning was that organic production remained a small part of US production (2% in 2002), with the potential to rise to 10%. They argued that it would need to rise to 23% to achieve the same overall benefit as an entirely integrated industry. This point is of significance to New Zealand production, where the production system was observed to consist of an integrated regime and an organic regime, with conventional production - as understood in US production - permanently superseded (firstly by IFP, and more recently by PipSure and Pipsafe).

Soil health and fertility parameters for organic farms operating under Bio-Gro[10] and biodynamics protocols in New Zealand have been reported (Condron *et al.*, 2000) alongside a review of early studies into soil health under long-term organic practices. The authors reported that soil organic matter and soil biological activity were found to be generally higher in organic farms than in conventional, but that questions remained over the replacement of nutrients under biodynamic systems. They found that farms operating under the Bio-Gro protocols had the potential to be sustainable.

An undergraduate honours thesis (Poe, 2003) compared the energy use of conventional apple production and organic production[11]. The work is interesting and valuable in the context of my research. Poe (2003) found that organic production was more intensive per mass of product and per planted area than conventional production. She also observed that the use of nitrogenous fertilisers was a significant determinant in the resulting values of energy indicators. This observation resulted in specific attention being given to urea in the orchard energy study (Sect. 3.3.1 and Sect. 3.2.1). Her results were certainly site specific, but even so they constitute a useful contribution to the literature of energy use in apple production.

2.5.2 Integrated production protocols

The NZ pipfruit industry introduced a version of integrated pest management in 1996 as part of its integrated fruit production (IFP) programme. This has since been renamed PipSafe. PipSafe and a parallel low residue programme (PipSure) are widely adopted in NZ fruit production, the earlier IFP programme achieving acceptance by 100% of non-organic growers by 2001 (MAF, 2007). Production systems in New Zealand were classified as organic fruit production (OFP) or IFP (at the time of the farm study), and accredited by stringent auditing processes. However, the IFP programmes observed (Sect. 3.2.1) were not prescriptive, but were interpreted as a spectrum of management practices, constrained by the specifications of individual markets. The bio-security standards of the US and some Asian markets for example required higher pesticide inputs than programmes approved for European markets.

---

[10] BioGro is a registered organic production protocol for which growers can be certified.
[11] On the Ricker Hill Farm, Turner, Maine.

2.5.3 An LCA study of New Zealand apple production

Mila` i Canals (2003) reported an LCA study of New Zealand apple production systems as part of a broader investigation. The author's overall objective was to investigate the application of the LCA methodology to agriculture to improve understanding of both agricultural systems themselves, and to contribute to the methodological development of LCA. His study of New Zealand apple production consisted of the application of current LCA practices using the ISO 14040 standards to collect data from orchards utilising both IFP and OFP production regimes. The study compared data from three IFP orchards, two OFP orchards and four sets of industry average reference data, the data representing two different regions (Hawke's Bay and Central Otago).

Energy data was observed using a process-based methodology, recording the number of occasions orchard operations were conducted. The energy inputs were derived from this data. A comparison of this methodology with the survey methodology adopted by Wells (2001) is presented in Ch. 3.

Mila` i Canals (2003) concluded that site-dependent characteristics had a greater bearing on the results of the LCA study than any of the main variables (OFP v IFP or regional differences). The author found that orchard practices such as the use of particular types of machinery (e.g. mobile hydraulic picking platforms, or 'hydra-ladders') or variations in pesticide or fertiliser used, significantly affected the outcome of the study.

The significance of this study to apple energy research is that:
- It measured, and provided case study data for orchard energy usage,
- it identified large differences between sites, and
- it identified energy consumption as a significant component of environmental impact.

The finding of wide variation between sites underscored the need for the orchard component of the present study to observe a larger sample group than that study. The depth of the study was also important, as the author considered aspects of

sustainability from a wide range of perspectives, including global agricultural production. The author also considered the relationship between an increase in production intensivity and sustainability. He argued that while an increase in intensivity might appear to offer advantages in terms of the volume of product produced from a unit of land, the long-term effects might result in an increase in environmental degradation, with specific reference to soil degradation. That was an important argument, as intensification is widely adopted as a strategic direction for agriculture, and has been proposed (Wilson, 2005) as a strategy for the New Zealand apple production industry.

An advantage of the process-based methodology employed by Mila` i Canals (2003) was that energy usage could be specified or modelled for orchard processes. It could however result in significant errors in measured energy consumption at the site level.

His empirical results were not intended to be interpreted as benchmarks the industry as a whole, but his conclusions were claimed as valid for a more general application of LCA methodology in agriculture. He concluded (p 147) that:

"the intensive mechanisation of field operations has been found to seriously hamper the environmental preference of OFP over IFP in New Zealand."

That conclusion could be challenged on the basis of the study's small sample size. It also inferred a presupposition that OFP is intrinsically 'better' than IFP. The present study has not challenged that presupposition, but neither has it accepted it as necessarily valid. Mila` i Canals (2003, p 139) anticipated the criticism by explaining his underlying conclusion:

"current criteria for organic agriculture do not cover so far important aspects that hamper the environmental sustainability…"

The main conclusions of this author were, as claimed, a contribution to the development of the agricultural LCA methodology, and the depth of the investigation made it an important precursor for my study. A subsequent examination (Mila` i Canals et al., 2006) of his original sample group concluded that:

"more than 50% of most impact category results considered in the study are due to energy-related emissions."

These authors consequently advised that energy consumption should be considered in the design of certification schemes, advice that appeared to be directly targeted towards OFP and IFP protocols. They noted the significance of mechanisation in NZ apple production, and reported total energy consumption (425-700 MJ t^{-1}) differentiating "input items" (mechanisation, machinery, fertilisers, pesticides and herbicides). They also reported energy consumption for field processes. The bottom-up process methodology adopted in that study provided a level of detail that was not available from the top-down approach of my study. However, the total energy consumption values must be regarded as less reliable in terms of industry benchmarks than the values reported in my study (see Ch. 3 for further discussion.)

2.6 LCA and related analytical and sustainability approaches

A range of approaches have evolved, or been proposed by researchers to measure or assess sustainability in agricultural systems. Some of these approaches have proven particularly useful to the agricultural sector, including energy accounting, carbon accounting (Lal, 2004) and sustainability indicators. Life cycle assessment (LCA) has achieved a dominant status among these approaches.

2.6.1 LCA

LCA has attained widespread support as a more holistic approach. Ny (2006) described LCA as (p16):

"one of the most rigorously developed and frequently used"

tools of the emerging discipline of industrial ecology.   It has been specifically applied to the context of agricultural food production (Cowell, 1998, Mattsson, 1999). It has evolved into what is arguably the default methodology for assessing issues of environmental sustainability in agricultural production, exemplified by its adoption in government reports such as the DEFRA food-miles study (Smith *et al.*, 2005).

Prescriptive LCA practice is now defined in the ISO 14040 series of standards, however its scientific basis has also been examined in a practitioner's handbook (Guinée *et al.*, 2002).   This author previously described the generalised procedure for LCA (Guinée *et al.*, 1993), describing a linear process (p 2):

- goal definition
- inventory description
- classification of inputs and outputs
- valuation and appraisal
- improvement analysis.

The existence of feedback loops was acknowledged, but omitted from the early model. However, the description of LCA recognises that a product system is to be analysed rather than a product per se. A key theme enunciated as a description of LCA is the term 'cradle to grave' (Wenzel *et al.*, 1997), reinforcing a perception of LCA as a linear process. Some systems concepts, in particular boundary definitions and boundary judgments are incorporated in this early description of LCA practice. However a criticism can be made that the scientific philosophy underlying LCA was explored subsequent to the establishment of the methodology itself. The early history, and the presuppositions of LCA are examined later (Sect. 4.3).

Heiskanen (2002) examined life cycle thinking, arguing that LCA, while being represented as an "objective, scientific method" in fact draws on other disciplines and derives meanings by negotiation between actors. She argued that not only has LCA evolved, but that life cycle thinking has become imbedded in organisations and society. She claimed that LCA-based ideas and tools represent an emerging institutional logic.

Finnveden *et al.*, (2009) provided a review of recent developments in LCA, offering a summary of the main achievements of, and the challenges faced by LCA. They distinguished between attributional and consequential LCA. The authors supported the view that a primary purpose of LCA is to support decision making, and that by implication LCA is strongly linked to intervention. They considered the difficulty of feedback mechanisms, recognising systems models as a potential tool for predicting

future impacts. They reported the use of normative scenario models as a valid method within LCA.

Their discussion of system boundaries, following Guinée *et al.*, (2002) recognised boundaries between the technical system and the environment, between significant and insignificant processes and between the technological system under study and other technological systems.

2.6.2 Issues in the use of LCA

Boundary definitions and judgments constitute a consistent challenge and dilemma for LCA practitioners. While practitioners are invariably aware of them, and in many cases acknowledge them or even seek to resolve them (Giampietro, 2004, Werner, 2005), the existence of a standard methodology and proprietary software may lead to inadequate attention being given to assumptions and boundary decisions. The risk in this approach is that reported findings from LCA studies may be used to drive interventions, and that those interventions interact strongly with factors lying in areas of uncertainty.

The approach proposed herein is for the LCA practitioner to take a higher level of ownership of the intervention stage. The proposed methodology adopts methods that more readily gather 'soft' information, and integrates that information with information derived from LCA prior to intervention (see Sect. 4.4).

2.6.2.1 Allocation in LCA

Procedures for allocating impacts are detailed in the ISO 14040 series of standards. General direction is given that system expansion is preferable to allocation, but that where allocation is unavoidable it can be performed on the basis of economic or mass units. Allocation has become the subject of a body of discussion and debate. Some of the key findings of this thesis were anticipated in a broad-ranging discussion of issues in the context of the attribution and allocation of emissions (Werner, 2005). Werner (2005) defined allocation as (p9):

"the partial attribution of the material- and energy flows of a shared or joint process to the product under study according to specified allocation rules."

A statement he made in his conclusions to a discussion of end-of-life options for wood products encapsulated his thinking (p327), and could be adopted as a theme of the present thesis:

"there is no simple answer to a simple question in a complex context."

His discussion was limited to product LCA. Nevertheless the issues the author described, and his interpretation of them, are consistent with issues identified in my examination of a food production system. The author focused on the relationship between mental models and causal relationships, basing his criticisms on the requirements of the ISO 14040 series of standards. In his introduction, he argued the impossibility of achieving unambiguous, objective, repeatable measurements of energy and material flows through LCA. He described LCA as transdisciplinary, refuting the feasibility of an empirical approach, and identifying the necessity to recognise mental models and value choices. He evaluated group model-building as an alternative methodology in the context of an LCA. He required modelling characteristics of LCA to address the characteristics of the decision situation, specifically the material and market characteristics of the subject. He further required consistency in applying mental models and values, particularly in boundary definition and the implementation of "causal relationships". A point this author made that is significant to the themes developed herein is that he identified the influence of changes within the socio-economic system over time as a source of uncertainty.

Werner (2005, ch.18) described allocation problems associated with the recycling of railway sleepers that reflected the issues identified in Sect. 4.2.3 pertaining to the treatment of energy in the utilisation of waste biomass in packaging. With respect to the classification of recycled timber he wrote (p249):

"The classification becomes even trickier if thermal utilisation has to be classified. When is the incineration of post-consumer wood considered under the aspect of waste treatment; or when would it be classified as thermal recycling…"

Werner (2005) has contributed significantly to the theory underlying LCA practice. His arguments were consistent with the philosophical themes developed in my study, and provided support for them.

The treatment of allocation for wood-based products has been recognised as being problematic, the influence of alternative procedures being highly significant (Jungmeier *et al.*, 2002). Emissions may be allocated by several means, Jungmeier *et al.*, (2002) reporting mass and economic allocation as the most common, with mass and volume being recommended for forestry; mass, volume and proceeds for sawmills, and mass and proceeds for wood industry. These authors focused on the bi-functional nature of wood products. They considered the use of wood products (and co-products) as structural materials, and also, at various stages in process chains, as an energy source. Basing their investigation on the procedures outlined in ISO 14041 (superceded since by 14044) they considered an allocation approach that partitioned multiple inputs and outputs and recycled components. They recommended avoiding problematic allocation by expanding the system (to include energy for example), or a substitution method where equivalence to non-wood products was based on energy content. They acknowledged that other forestry "functions" such as recreation and bio-diversity were not considered.

2.6.2.2 Framing and values in LCA

An area of discussion developed in LCA literature prompted by a political response to a scientific examination of the toxicity of chlorine in the Netherlands. A Dutch government minister was reported to have made a decision based on indicators generated in an LCA study, a decision that ignored the conditions expressed by the study's authors.

Bras-Klapwijk (1998) highlighted the lack of transparency in quantitative indicators and the risks inherent in the division of tasks between policy makers and scientists. This author further argued that since LCAs are based on a rational frame, characterised by a comprehensive, means-end nature and an emphasis on formal, quantitative methods that they (LCAs) provide apparently objective results that allow policy makers to over-simplify arguments. A refinement of LCA methodology was proposed in which a stage would be inserted between goal definition and inventory

calculation. This stage, involving "scientists and others", would explore "values and frames". An issue that was not fully explained, was that if the LCA frame, which was argued to be constrained to a rational approach by clearly defined methods and procedures, were found to be inappropriate in a specific case, there would be no clear mechanism for proceeding within an alternative frame (such as a precautionary frame).

Tukker (2000) examined the philosophical basis for LCA in the context of the Dutch toxicity debate and PVC production in Sweden (Tukker, 1999). He argued that LCA assumes a positivistic view noting that this view further assumes an understanding that knowledge derived in LCA inventory construction is value-free and that scientists should have a key role in the process. He compared the traditional positivistic model with a "constrained relativistic" model. Tukker (2000) described three distinct "frames" (representing descending confidence in traditional positivistic science): the classical risk assessment approach, a strict control approach acknowledging the limitations of risk assessment (RA), and a preventative, precautionary approach.

Tukker (2002) further examined these frames offering an approach for moving forward with LCA and RA methods while "honouring" the other frames even though they might lead to irreconcilably different end points. He offered an indicator approach that categorised system and substance related uncertainties.

Finnveden (1997) discussed the inclusion of moral and ethical considerations in LCA, acknowledging that such considerations are seldom discussed. He distinguished valuation as an LCA procedure, separate from classification and categorisation, and reviewed ideological standpoints that would determine how weightings might be assigned (or not be assigned) to LCA derived data. This author demonstrated the extent to which ideology underlies LCA valuation procedures, including consideration of the moral attributes of nature, aspects of justice, economics and philosophy.

Although he did not question whether it is valid to separate valuation from classification, he did argue that a single indicator LCA study (offering energy requirements as an example) is a form of valuation, as a prior decision to exclude other forms of indicator has been made.

A decision conferencing approach combining LCA with multi-criteria decision analysis (MCDA) has been shown to advance the capability of LCA in providing decision support in a situation characterized by high levels of complexity and uncertainty (Elghali *et al.*, 2006). This extension of the scientific method provided a mechanism for weighting incommensurate impacts, including some impacts such as "socio-economic disruption" that embody normativistic elements. The method is arguably appropriate for LCAs of limited scope (in this example supporting decisions over the incorporation of recycled materials in roading maintenance). The authors acknowledged the need for a systems approach, and recommended further development of the method. The method certainly defined broader boundaries than some earlier LCA studies, however it is argued to be a refinement of a reductionist approach rather than a true systems approach, as systems concepts such as feedback mechanisms and emergence would require further methodological attention.

2.6.3. Other approaches

A comparative study (van der Werf and Petit, 2002) described 12 separate indicator-based methods (including two variations of LCA). Pretty et al (2005) included ecological footprints in an outline of sustainability approaches.

Finnveden and Moberg (2005) reviewed a range of environmental study tools, categorizing them with respect to whether they are procedural or analytical, descriptive or change orientated, and by the types of impacts and the object of the study. The range of tools reviewed is not claimed to be exhaustive, but was selected in consultation with the Swedish Environmental Protection Agency. Of these tools, those discussed further here are selected on the basis of their specific relevance to the present work.

Material flow accounting (MFA) is reported to represent a family of methods primarily concerned with the movement of materials. Its focus is broader than the product or process focus of LCA, but the accounting approach overlaps the inventory stage of LCA. Some of the inputs to the present study (e.g. fertiliser) adopted data derived from this family of methods. Kytzia *et al.*, (2004) reported the extension of

this method, incorporating economic data, to provide deeper understanding of a food production chain.

Environmental impact assessment (EIA) is a well-established method also represented by a range of related and derived methods. It is generally site specific and project orientated. While it was not suitable for the present broad industry assessment, its strategic derivative (Strategic Environmental Assessment) could be deployed at the strategic planning stage as a consequence of the present study.

Ecological footprint methods apply impact data to land area. This may take the form of the impact data associated with land within geographical boundaries, or it may predict the land area required to assimilate measured emissions.

Carbon footprinting has received widespread public recognition, but its development has been driven by non-governmental organisations rather than the scientific community (Weidema *et al*., 2008). The objective of carbon footprinting is to present a single, easily understood indicator providing a comparative value for global warming impacts. Non-carbon emissions may be considered, but are presented as CO_2 equivalents. In comparison to LCA it can be criticised as over-simplified. Carbon footprinting was reported to conform loosely to LCA principles (defined in the ISO 14040 series) in areas such as boundary definition and allocation, but was more definitively supported by a British standard (PAS 2050).

2.6.3.1 The Natural Step – a sustainability framework

The natural step (TNS) framework is included in this review despite a level of controversy surrounding its credibility as a purely scientific framework, due to the commercial structure in which it is promulgated, and the 'evangelical fervour' of some of its proponents. It is given specific attention here because of its fundamental approach. Its recognition of thermodynamic principles is highly relevant to this investigation of energy inputs in an organisational sustainability context.

Robert (1997) is representative of a large body of work by the author (Karl Henrik Robert) who was the founder of the Swedish organisation The Natural Step (TNS). Swedish scientists worked to reach a consensus on the core conditions required to

achieve sustainability (Upham, 2000). The principles they proposed were based on the laws of thermodynamics, recognising that the earth is essentially a closed system for matter, but an open system for energy. The Swedish group agreed that the better organised matter is, the more valuable it is, and that the only natural mechanisms for increasing order are driven by the sun. The TNS framework has received limited academic recognition and support, but it should be recognised as the framework that best describes the thermodynamic requirements for sustainability. The TNS framework recognised four system conditions for a sustainable society (Robert *et al.*, 1997):

- Nature is not subject to systematically increasing concentrations of substances extracted from the Earth's crust,

- nature is not subject to systematically increasing concentrations of substances produced by society,

- nature is not subject to systematically increasing degradation by physical means,

- people are not subject to conditions that systematically undermine their capacity to meet their needs.

TNS constitutes a basic frame of reference for organisations to make strategic decisions that lead toward sustainability. In a comprehensive review of the suitability of the TNS framework as a measurement of sustainability, Upham (2000) reported qualified academic support for the TNS concept. Criticisms reported by this author include the lack of threshold conditions. TNS conditions have been defined in terms of "systematic progression", assuming perhaps that many of the relevant thresholds have already been passed. Because TNS was defined in the most primitive thermodynamic terms, its application to real systems is not prescribed, and its core conditions are frequently difficult if not impossible to achieve (Upham, 2000).

A consensus report to TNS (Engstrum *et al.*, 1990) provided a comprehensive explanation of the nature of energy and environmental degradation in Earth's ecosystems. These authors argued strongly that modern civilisation must develop a new energy consumption paradigm that rejects both fossil fuel and nuclear energy as the dominant drivers of civilisation.

With respect to the TNS framework, Upham (2000, p 454) concluded:

"its structure is found to be significantly rhetorical and its implications highly precautious in some respects, while being inadequately precautious in others…ultimately, judging whether TNS merits the wide audience that it seeks requires value judgments on how much evidence of global environmental damage is needed to justify mitigatory action, what degree of action is sufficient, and whether some rhetorical use of science is justified in circumstances of unsustainable trends."

However, despite the qualified support of Upham (2000), the TNS framework is valuable if not unique. TNS sits outside the norms of academia in that it is a commercial, political and perhaps popular movement. Nevertheless the thermodynamically defined core conditions have provided an almost irrefutable absolute reference point that has not been addressed as precisely elsewhere.

2.7 A philosophical perspective

A contributor to systems thinking (Midgley, 1997, Midgley, 2000, Midgley, 2003) provided arguments and discussion that placed the perspectives of the philosophers of science, and the architects of systems thinking, in a coherent framework. This author strongly supported the need to consider scientific philosophy in scientific research, and refuted the argument that philosophy is not relevant. He dissected the contribution of Popper (as well as the philosophers Kelly and Habermas), and placed limitations on the circumstances their principles were able to inform. He reported case studies conducted in the field of social science, however he expressly identified the issues of global climate change and sustainability as issues that exemplify interconnectedness, and thus require a systemic approach, particularly with regard to intervention. He has provided a generalised framework for the treatment of research encompassing ethical judgments. His philosophy and practical approach have been identified here as a leading contribution to systems thinking, providing a theoretical basis for a proposed development of LCA methodology (Sect. 4.4).

2.7.1 Introduction to philosophical perspectives

At least one philosopher has directly addressed the ethical and philosophical foundation of food-energy relationships (Johnson, 1984). He argued that (p151):

" the concept of a product is normative. Technically, all inputs that enter a production process come out. Part of the output possesses the property of goodness; this part is called product. Those parts that are valueless are called wastes. Those parts that possess the property of badness are also called wastes, but are further identified with such terms as pollutants, noxious wastes, etc."

He continued to explain that to think of ratios such as energy indicators as technical, value-free positivistic knowledge would in fact be meaningless. Nonetheless he argued that positivistic research, which he regarded as the overriding domain of scientific inquiry, has an essential place in food-energy research. He argued further that the outcomes of positivistic studies, such as energy indicators, were not sufficient in themselves to provide a basis for problem solving or decision-making.

Johnson (1984) held that the dominant philosophy of the biological and physical sciences is logical positivism, where experience and logic are the criteria for decision making. He implied that scientific philosophers regard logical positivism as obsolete, but that scientific practice has yet to respond to this guidance. He advised that normativistic[12] approaches could be regarded as providing objective normative knowledge; an achievement that has been considered impossible by logical positivists. He preferred pragmatism as providing a way forward by dealing with positive and normative knowledge simultaneously, but conceded that in practice it could prove cumbersome.

An alternative, and arguably acceptable practice he described is for positive and normative knowledge to be derived independently, and used together to solve problems. This conclusion constitutes the philosophical support for the proposal in Sect. 4.4 for a more systemic overarching approach to LCA methodology.

This author also discussed the significance of market and price systems. Monetary values were argued to reflect consumer value judgments, and provide information beyond that contained in energy units. In my study, energy studies reported in

---

[12] Normativistic science takes the position that knowledge of the goodness or badness of situations is a valid and necessary precondition for prescriptive knowledge.

monetary terms were found to be of low utility because they do not retain their meaning over time or in settings other than their primary context. However, Johnson (1984) identified the need for common currency as a critical requirement for making ethical judgments. The present study has identified (loss of) biodiversity as a common currency for decisions impacting food supply chains and sustainability.

Johnson (1984) identified food-energy research as a domain that is inherently value-full, demanding multi-disciplinary methods built on philosophies that give adequate regard to normative knowledge in the key areas of identifying assumptions, solving problems or building strategies.

2.7.2 Scientific philosophy and systems thinking

Midgley (2000) argued that while philosophy is commonly regarded as standing above methodology in a hierarchical sense, and methodology above practice it is preferable to regard philosophy, methodology and practice as "mutually supportive". This view is undoubtedly more sophisticated than the hierarchical view, but even so the simpler view of philosophy underlying both method and practice is the premise of this chapter. The present discussion challenges some of the norms of scientific observation and intervention in the context of sustainability issues, and with particular reference to sustainability indicators. It is argued that such a challenge should be built on first principles, and that those principles are embodied in the thinking of the philosophers of science. The literature of systems thinking has paid close attention to scientific philosophy, and the discussion here follows that pattern. Three philosophers (Popper, Polanyi and Bohm) have provided principles that when applied to food supply issues (Johnson, 1984), provide a fundamental basis for the arguments developed herein concerning presuppositions embodied in indicators derived through LCA methodology.

2.7.2.1 The nature of scientific knowledge

Of particular relevance to the present work is an explanation of how scientific knowledge is built (Popper, 1972) . This philosopher argued that problems precede observations (rather than vice versa) and that (p258):

"The growth of knowledge proceeds from the old problems to new problems, by means of conjectures and refutations."

He further argued that knowledge is gained by conceiving an inadequate explanation, and then criticising or refuting it. He presented an inverse analogy between the "evolutionary tree", in which species diverge over time, and the "tree of knowledge", in which divergent knowledge converges to unified theories. Popper (1972) also discussed the notion of objective truth, a concept that has considerable relevance to the nature of knowledge in the present field of study.

The key philosophical principle inferred from Popper (1972) is a paradigmatic pattern of scientific knowledge-building that is so obvious that it is seldom articulated. That is, that the findings of scientific work, having been examined by peers and remaining unfalsified, become the building blocks for future science. This principle is of crucial significance to sustainability studies, where numerical indicators are constructed in part from 'truth' in the form of unfalsified published values derived from earlier studies. Issues can potentially arise where the assumptions of a particular value are not fully known, and an accumulative effect occurs where that value, with its assumptions, is built into subsequently published work.

2.7.2.2 The nature of the universe and systems thinking

A significant early contributor to quantum theory has subsequently extended his contribution from physics to the philosophical arena (Bohm, 1980). This author offered new insights into the nature of the universe itself that constitute a significant advance to modern scientific philosophy. The thinking of Bohm (1980) is reflected strongly in more recent work closely aligned to the present field of study (Giampietro, 2004), and is consistent with the philosophies of at least some systems thinkers (Beer, 1984, Midgley, 2003). Bohm (1980) explained that our entire mode of thinking is based on the notion of matter consisting of discrete particles, a model that he rejects as inconsistent with the wave – particle duality of quantum physics.

Bohm (1980) introduced his concept of implicate order. He wrote extensively about the wholeness and interconnectedness of matter, expressing interconnectedness as a logical ramification of quantum theory and offering a number of sophisticated

analogies to demonstrate his insight. The author described matter as existing in a flow, or enfolding-unfolding flux. He acknowledged an affinity of his ideas with Eastern traditions of thinking rather Western. This link with Eastern traditions is also reflected in the work of some systems thinkers (Beer, 1981).

The 'connectedness' of observer and observed is a theme that is developed further by Midgley (2000). The concept has ramifications for the sustainability context of my study, and for the LCA methodology.

2.7.2.3 Tacit knowledge

An earlier philosopher introduced the subjects of personal knowing and tacit knowledge (Polanyi, 1958, Polanyi, 1966). This influential author argued that knowing is a personal process, and that knowledge is built on the personal framework of experience, skill and even emotion that constitutes human experience. He further argued that observers cannot separate themselves from the observed. Polanyi (1966) developed the concept of tacit knowing, holding that individuals know a great deal more than they can articulate, and that knowledge that can be articulated depends on a bank of tacit knowledge that cannot be expressed.

The concepts expressed by Polanyi (1958) provide support for arguments developed herein: firstly as direct support for understanding the nature of knowledge reported in the present field of study, and secondly, as inferred support for a parallel model describing knowledge encompassed in a field of study, and tacitly 'owned' by a contemporaneous scientific community.

2.7.2.4 The philosophy underlying the present research

The relevance to the present study of the principles espoused by these thinkers (Bohm, 1980, Johnson, 1984, Midgley, 2000, Polanyi, 1966) is that:
-   Knowledge is built on other knowledge; knowledge that contains elements that the builders of that knowledge were not aware of, and could not articulate,
-   the elements of this knowledge are connected to each other in unknown ways, and
-   food-energy studies are further complicated by tacit normative knowledge that may not be understood and acknowledged by the researcher.

Having established that global food chains are characterised by a high level of complexity, extending beyond the fields typically associated with the application of scientific method, we proceed to examine the nature of that complexity. Systems thinking has provided an approach for understanding complexity, and provides methods that would supplement LCA methodology.

2.8 A systems perspective

A general systems theory has been proposed and articulated (von Bertananffy, 1950). A key insight was that the interactions between system components result in the property of emergence - a property that is not predictable from the characteristics of the components as revealed in reductionist study. This author also provided a general explanation for the appearance of identical developments or isomorphisms, such as growth following an 'S' curve in subjects as diverse as the science of biological organisms or species, and the study of economic growth or chemical reactions. Modern systems theory has not universally endorsed all of this author's thinking, but nevertheless he is regarded as one of the 'fathers' of systems thinking. Following a general description of the universality of systems, he made a statement that could be regarded as a tenet of systems theory (p 108):

"There exist therefore general system laws which apply to any system of a certain type, irrespective of the particular properties of the system or the elements involved."

This author's work underpins a number of concepts explored in the current study, particularly the imperative to examine global food supply chains from a systems perspective.

A subsequent contributor has developed systems thinking, offering a broad perspective (Churchman, 1972, Churchman, 1979). In an argument espoused by myself (Frater and Houston, 2008), Churchman (1979) was identified as providing a general systems context for food-energy research. In a discussion of scientific research, Churchman (1979) confirmed the location of areas of study such as astronomy, geology and archaeology - in which there is no physical laboratory and in which the scientist cannot manipulate the variables - within the context of scientific research. In my research where there is no laboratory, Churchman (1979) required the

researcher to apply careful controls and to attempt to eliminate nuisance variables and observer interference in order to develop an understanding of the system.

Churchman (1979) went on to warn that the extension of the scientific method into the planning arena through experimental interventions was dangerous and potentially immoral. This warning of moral implications for systemic interventions is a theme that is reinforced in systems literature (Midgely, 2000) and is clearly relevant to the present research if it is to inform strategic planning decisions. Churchman (1979) explained that data provide a linkage between systems. In the case of energy data, linkages might be provided between the apple growing system and the physical environment system, and between energy supply systems and human social systems.

Contributions of the philosophers of science and systems thinkers have established that any perceived gap between physical systems and human systems is not real, and that intervention in one of these areas will inevitably permeate into the other. Systems practice has sought to bridge this perceived gap. Researchers have developed characterisations in order to understand and distinguish various types of system, and to understand interactions between them.

2.8.1 Hard and soft systems

A dichotomy in situation types has been characterised by five different authors (Rosenhead and Mingers, 2001): Ackoff distinguished between problems and messes, Rittel between wicked versus tame, Schon between swamp versus high ground, Raverts between practical versus technical and Checkland between hard versus soft systems. The present discussion has adopted the formulation of 'hard' and 'soft' systems, but in doing so recognised that this was representative of a dichotomy that could be represented by a range of analogies and terminologies.

2.8.1.1 Hard systems approaches

Hard systems deal with interacting variables such as those encountered in scientific, business or economic studies (notwithstanding the arguments already made regarding normative knowledge underlying food-energy science). They can frequently be expressed as a mathematical language.

A seminal contribution to system dynamics typified the hard systems approach (Forrester, 1961, Forrester, 1968). Forrester (1968) described the ubiquity and pervasiveness of systems, and introduced the concept of system dynamics (SD). He outlined the nature of positive and negative feedback loops, describing their characteristics and the mathematical principles that define them.

The hard systems approach can be seen to provide an accessible interface with normal scientific methods. The approach of Forrester (1968) was a scientific method relying on mathematical logic, and was not originally concerned with the human domains of value judgments or ethical concerns. Subsequent researchers (Hjorth and Bagheri, 2006) have described the evolution of the SD approach to a stage where models might address the system properties of (p 74):

"bounded rationality, limited certainty, limited predictability, indeterminate causality, and evolutionary change."

These objectives have extended the perceived limits of the SD approach to sustainability studies to the point where the method takes significant account of the fundamental systems property of emergence. Hjorth and Bagheri (2006, p 79) explain that it is not the task of an SD model to predict the future, but rather to:

"give a valid description of possible system behaviour under a given range of conditions…"

The SD approach draws on the language of systems theory, and takes account of the system theorists such as Ackoff and Beer, yet its methods deploy computer modelling to predict possible system states. The anomaly here is that computers are driven by mathematical logic, and cannot be assigned moral responsibility, or be asked to form normative judgments, yet they can model behaviour which is itself driven by human values. An economic SD model (Hjorth and Bagheri 2006, p 87) included influences such as "level of life standards" and "demand for life services" that clearly contain value-rich assumptions and boundary judgments. While SD remains the most sophisticated of the hard systems approaches, it has provided mechanisms that take account of at least some soft systems thinking. Hjorth and Bagheri (2006) are

therefore justified in presenting SD as a methodology that might be used to find management solutions that bridge the gulf between hard and soft systems.

Causal loop diagrams (CLD) are commonly regarded as a basic tool of system dynamics (Morecroft, 1982). This author attributed the concept firstly to Forrester (1961, 1968) but credited its distillation and popularisation to subsequent research (Goodman, 1974). Morecroft (1982) criticised the CLD method as weak, offering the subsystem diagram and the policy structure diagram as alternatives. However, the term CLD was used more recently by Hjorth and Bagheri (2006); the technique itself having evolved since its early appearance.

The notion of computer models sufficiently sophisticated as to drive interventions into environmental or human social and political systems must be treated with great caution. The checks and balances for such interventions have been provided (Midgley, 2000, Ulrich, 2001). (A combination of these methods is proposed in Sect. 4.4 as a suite that would advance the management of interventions into global food supply systems when integrated with LCA practice.)

2.8.1.2 Soft systems approaches

The application of soft systems theory has been described (Checkland, 1985, Checkland and Scholes, 1990, Checkland, 1999, Checkland, 2000). Soft systems theory deals with issues such as human or social issues, and more specifically the 'messy' problems of management. Describing hard systems theory, Checkland (2000) reported that (p11):

"it was supposed that this would provide a meta-level language and theory in which the problems of many different disciplines could be expressed and solved."

Checkland (2000), made a crucial distinction between enquiries into the complexity of our world and enquiries that were (p17):

"applied to the process of our dealing with the world."

Checkland (1985) argued that although the tradition of hard systems and the tradition of soft systems were complementary, hard systems were a special case of soft systems. (Checkland, 1999) described systems in terms of the study of meaningful human activity. That activity might be, but was not limited to goal seeking. An observation with respect to agricultural systems is that while lower level elements of the system are definitely definable in terms of goals (producing fruit, or marketing fruit), at a higher level goals are less easy to define, and are observer dependent. This has been reflected in the different points of view of scientists working from a perspective that was predominantly concerned with Southern Hemisphere production and exportation (Saunders *et al.*, 2006) and scientists working from a perspective that was predominantly concerned with the food requirements of a European community characterised by its unique demographics (Stadig, 2001). Checkland (1999) continues to develop this point: that a systems model will vary according to the frame of reference.

Different viewpoints can be regarded as a filter, but what is clear is that differing frames of reference will generate different models. Conceptually, a system can be argued to exist independent of the observer (an argument elucidated in its rawest form by Popper (1972, p301), but disputed by Polanyi (1958)). However what we are discussing here is the study and modelling of a system, which inevitably requires us to define a window through which the system is observed. Giampietro (2004), drawing on Bohm (1980), required the observer of agricultural systems to define multiple viewpoints in order to generate a rich enough model to genuinely represent reality.

The subject of the relationship between the observer and the system, and subsequent models of the system, has been regarded as highly significant by systems writers and philosophers of science. The relevance to the present research is that the selection of a method and the construction of sustainability indicators require the observer to take a position or viewpoint. Some of the constraints of this viewpoint would be explicitly identified in the form of boundaries, but others would be tacit value judgments. If those value judgments were not explicitly identified, then the adoption of the indicators in new research would become progressively compromised.

Total systems intervention (TSI) was introduced as a tool for creative analysis and intervention into complex systems (Flood and Jackson, 1991). These authors contributed a robust methodology for enquiry and intervention in soft systems problems such as those encountered in the management of organisations. The method was subject to intense scrutiny, criticism, experimentation and further development (Checkland, 2000, Flood, 1995, Midgley, 1997). TSI was not pursued further in my research, but was noted as relevant and potentially useful, and was identified as a potential direction for future research.

The relevance of the soft systems approach is that food-energy systems embody characteristics typical of both hard and soft systems. The LCA approach is a hard systems method of enquiry (Sect. 4.3), generally ignoring soft systems issues, or deliberately or implicitly excluding them during boundary construction. The following section leads to the identification of *critical system heuristics* (CSH), a tool that provides a mechanism for assigning a proper level of attention to soft issues in LCA.

2.8.1.3 Intervening in systems

An area of discussion in systems literature surrounds the selection of appropriate methods for studying, analysing and intervening in systemic problems. Basing his arguments on the principle of interconnectedness, Midgely (2000, pp123-128) commented on the role of science itself in systemic enquiry, concluding that scientific observation can be a form of intervention. Hence, while Midgley (2000) addressed his arguments toward systemic intervention, he explicitly included scientific observation in his field of concern. Since my study focused on the presuppositions underlying scientific observation, knowledge building and intervention, the arguments presented by this author informed and impinged on the study at every level.

The author has previously explored this subject (Frater and Houston, 2008), concluding that the observation and reporting of energy data did indeed constitute a systemic intervention. The reporting of energy data in the popular press was provided as an example. In such cases, these authors identified a risk that the media or political interests might form value judgments beyond the authority of the actual research.

Ulrich (2001) discussed research competence. An area of specific relevance to my study was his treatment of assumptions. He argued that the limitations of any method were contained in the methodological and theoretical assumptions. He linked competence with awareness of the assumptions that underpinned a particular method, and even then questioned the researcher's right to make claims (p18):

"Even if a researcher remains thoroughly aware of the methodological and theoretical underpinning of his competence and makes an appropriate effort to make it explicit, does that mean that the research findings provide a valid ground for practical conclusions?"

The author continued to enunciate the critical importance of ethical questions in research in his principle of "the primacy of practice". That is, the researcher must place the human ramifications of research before methodological competence. His discussion on boundary judgments is critical and relevant to the present research. He introduced critical systems heuristics (CSH), an approach that he described as a framework for reflective practice (Ulrich, 2002a). A working paper (Ulrich, 1986), cited in Midgley (2000), listed twelve 'critically heuristic' questions in two modes ("is" and "ought") that provided a basis for his later thinking (Table 4.4.2).

Ulrich (2002b) described boundary judgments as conditioning (placing conditions around) value considerations and empirical observations, or "values and facts". Boundary judgments were regarded as an essential component of a reference system. He also defined *claims* and *merit* as essential terms or considerations within CSH. Within the CSH framework, where we might in everyday language speak of a 'relevant context', the author required us to confine or limit that 'field of concern' to an agreed reference system. Rather than a procedure or method, Ulrich (2002b) proposed a broad approach or an attitude. Even so, although he shunned the nomenclature 'method', he did provide 'guidance' at a level that could be considered a method if the practitioner were permitted to use the term. He described a systemic approach, consisting of an "eternal triangle" of facts, values and boundary judgments. To adhere to this guidance, each of these three vertices must be considered in the light of the other two.

The concepts of mechanism, reductionism and subject / object dualism were identified as "the enemies" of systems thinking, in a less than subtle challenge to Churchman (1979). With respect to subject / object dualism, Midgley (2000) preferred a model of "process and content", recognising that both subject and object are constrained by the same principles of boundary construction. This argument is synergistic with the argument presented by Bohm (1980), who argued that the status of subject and object permeates the entirety of Western thinking. Bohm (1980) went so far as to offer a new mode of language and thought (the rheomode) in order to redress the imbalance in Western thought, and place proper emphasis on process.

The arguments and frameworks proposed by these authors (Midgley, 2000, Ulrich, 1986, Ulrich, 2002a, Ulrich, 2002b) are fundamentally relevant to food-energy enquiries. This body of work represents a significant advancement of systemic thinking as a methodology for structuring scientific enquiry, and informs the methodological gap identified by Johnson (1984) for integrating positive and normative knowledge. CSH constitutes an approach (acknowledging that its architect expressed reservations about calling it a 'method') that would be able to be transferred to LCA methodology, especially at boundary definition stages, or when examining the presuppositions of prior research.

2.8.2 Other contributors to systems literature

The *viable system model* (VSM) was introduced in twin volumes (Beer, 1979, Beer, 1981) that applied the concept of cybernetics to management. This visionary author observed that organisations exhibit management interactions and processes that are quite far removed from their acknowledged management structure. He devised a general model that could be applied to describing, analysing faults or planning new organisational structures. Beer's work sits apart from hard and soft systems approaches. It offered a framework for understanding and imposing order on the messiness of management interactions, an approach that displays synergy with soft systems thinking. The VSM relies on Ashby's law of requisite variety (Ashby, 1952). The architect of the VSM (Stafford Beer) adapted the concept of algedonic feedback[13], a principle stemming from his work in operations management. The

---

[13] Algedonic feedback is analogous to a 'pain' reaction in a systems model.

understanding and management of feedback is synergistic with systems dynamics, and lends itself to mathematical modelling. It can be seen to be a precursor to modern models of artificial intelligence.

Stafford Beer experimented with methods of achieving stable biological systems modelled on Ashby's electromechanical device – the homeostat (Ashby, 1952). This device was configured to achieve stability through electromechanical feedback, and was simple enough in principle for Beer to attempt to model it, first with children, then with mice and lower organisms, achieving varied amounts of success.   Beer's application of this experimentation was his VSM. The VSM can be understood as an attempt to provide a model by which organisations could achieve stability. That is, that they would react automatically to changes in their environment, and remain stable (and therefore survive) over time (Pickering, 2002).

The VSM is significant in that it provides a mechanism for planning and analysing organisational structures. It constitutes an important component of a systems approach, and is identified as a method that can be adapted to agricultural organisations at any scale, from below farm level to global supply structures.

A further soft systems method *strategic assumption surfacing and testing* (SAST) (Mitroff and Emshoff, 1979) provided a practical mechanism for 'surfacing' (or making explicit) hidden assumptions. This method was therefore designed to take knowledge from a tacit state to an explicit state. Its original context was that of organisational planning. Its specific relevance is that it was adapted as a component of a proposed development of LCA methodology (Sect. 4.4).

2.8.2.1 Global systems thinking

In the concept of Gaia (Lovelock, 1989), Earth was described as a global "organism". This concept is synergistic with the VSM concept of recursivity, in that the global system was represented as functioning in a similar fashion to the recursive sub-systems within it. This author presented the earth as a system "seeking" homeostasis (Ashby, 1952). A particular point of view this author took, a view that is reflected in Giampietro (2004), was the critical importance of global biodiversity. The clearance of tropical rainforests was identified as "the vast, urgent and certain danger". A key

insight addressed was the interconnection of the geophysical, geochemical and biological scientific arenas. This author argued that top-down systemic observation is more appropriate for studying global systems than bottom-up scientific observation. He argued that it is critical to acknowledge and include the mechanisms by which organisms actively change their environment, rather than considering them to just adapt reactively.

Equating a top-down approach with a systemic approach is a point of view that isn't overtly supported by other commentators. However, there is some merit in this, as the top-down approach is effectively observing the emergent characteristics of a system. The examination of economic metrics in input-output analysis can be considered to be a 'black box' approach, aligned more with hard systems methods than soft systems.

The concept of Gaia is by no means universally approved within the scientific community, as it implies a level of self-consciousness on the global entity that is repugnant to normal science. However, this author has achieved significant influence the literature of sustainability; an influence that points to a perceived need to look outside of traditional scientific thinking for models that adequately explain the complex interactions between human activity and the biological and physical sciences.

2.8.3 Systems thinking in agricultural sustainability

A further original contribution (Giampietro, 2004) was identified as significant and relevant to the present field of study. This author examined the issues surrounding agro-ecology from a systems perspective, offering new approaches to the problems encountered in moving towards sustainability. His approach could be characterised as a sophisticated hard systems methodology, although his reasoning included a number of soft, human or social issues.

This work constituted a significant contribution to the field of agricultural sustainability. The philosophical framework was entirely consistent with my study, including explicit recognition of the need to study the agricultural sustainability context from a systems perspective. Giampietro (2004) offered a comprehensive methodology, with new methods and indicators that attempted to address the need to

incorporate multiple perspectives in agro-ecological sustainability indicators. A difficulty arose in that the methodology did not lend itself readily to integration with other approaches. Therefore my study only drew support from Giampietro's *reasoning* for the need to develop new approaches, and not the methodology itself.

Giampietro (2004) discussed the contrasting and even apparently conflicting views that could be gained of a system depending on the pre-analytical choices made in a study. He presented the mosaic effect, adopting an example from Bohm (1980). He described a fish tank filmed from two adjacent sides. If the images from each camera are relayed to screens in another room, the two views offer non-equivalent descriptions of the same system. Each view in isolation provided some useful information, but some observations could only be correctly interpreted when the two views were taken together. Similarly, systems could not be accurately represented by one-dimensional observations. Following an earlier philosopher (Rosen, 1985) he concluded that no one observer can ever see the whole picture. In a statement that reflected the thinking of Bohm (1980) he claimed that (p279):

"Science deals not with the reality but with the representation of an agreed-upon perception of the reality" and,

"Substantive models of real systems do not exist."

These statements challenged the assumption of scientific objectivity at a level beyond that of the present study, however it is clear that he is questioning the ability of traditional scientific thinking to provide an adequate understanding of agricultural systems.

Giampietro (2004) followed other systems thinkers in vilifying reductionism. He argued that attempting to reduce or reconcile disparate views into a single indicator results in invalid or meaningless measurements. His methodology addressed the need to consider a range of irreconcilable or conflicting views of a system when making judgments about sustainability. He also recognised consistent failings in literature dealing with the question of sustainability in agriculture (pp281-282):

"Although most studies recognise and describe the boundary conditions of a specific production system, and the inherent limitations imposed by those boundary conditions on production, they fail to explicitly describe how much room is left for intensification. Studies fail to characterise the basic strategies of the farmer. For example, is the farmer sustaining the rest of society, or being subsidised by society?… Studies fail to critically appraise the validity of their studies. For example the selection of a viewpoint implies missing other viewpoints, and potentially failing to question how widely the results can be applied."

His identification of intensification as a key issue informed the orchard energy component of my study (Sect. 3.2.1). His acknowledgement of social implications supported the adoption of soft system methodologies, and his recognition of a need for critical assessment was consistent with the views of Ulrich (1986, 2002a) and Midgley (2001).

Commenting further on the issue of depleted resources, in a statement that reflected the conclusion of Lovelock (2003) above, he stated (p365):

"In a way, the concern for the ecological impact of high-input agriculture should be, for the moment, much more worrisome than the concern for the limitation of existing reserves of fossil energy."

He continued to list water shortages and loss of biodiversity as crucial constraints that he placed before greenhouse warming, ozone depletion and the appearance of new diseases.

In common with other Northern Hemisphere researchers, Giampietro (2004) conducted research in developed US and European settings and third world settings. However, neither of these situations adequately addressed the role of New Zealand as a net exporter of agricultural commodities, where the boundaries of land and population bases supported by our agricultural activities are different from the boundaries containing the agricultural activities. Giampietro (2004) addressed the concerns of the pressure exerted by large populations on limited productive resources; an issue from which New Zealand is distanced, but not isolated. Part of the challenge

for my study was to provide a viewpoint that adequately reflected the frames of reference of both Northern Hemisphere and New Zealand stakeholders.

Giampietro (2004) argued that generalised conclusions should not (and cannot) be universally applied. I have extended that argument to claim that it is not only conclusions that cannot be universally applied, but also that the methods underpinning those conclusions can embody value and boundary judgments that are not universally valid. Giampietro (2004) reflected both hard systems methodologies and soft systems thinking. This combination is unusual in any context, and in the context of agricultural sustainability is rare if not unique. While his methodology wasn't adopted, his arguments related directly to the aspects of scientific philosophy, and the methodological questions explored herein.

2.8.4 Quality science literature

A quality science method (the Pareto chart) was adopted in the present study as a tool for identifying critical areas of energy usage to target for improvement. The Pareto principle (originally presented in the field of economics) was adopted to identify and present the critical areas of energy use (Rao *et al.*, 1996, p181). Quality methodologies have been widely reported in management literature, represented by a practitioners text (Rao *et al.*, 1996) and a volume that places quality science in the context of systems thinking (Beckford, 1998).

UK researchers (Simons and Mason, 2003) utilised value stream mapping (Hines and Rich, 1997) a method from lean thinking, a quality science approach, to analyse global food supply chains. New Zealand apples were a component of their analysis. These authors focussed more on the development of a typology, or decision-making process (p63) than their findings relative to the supply chains under investigation. They promulgated a line of thinking for my study that was critical to the philosophical and systemic issues raised, eventuating in the proposed methodology presented in Sect. 4.4.

I previously questioned the use in sustainability studies of a method derived from an entirely different sector of activity (Frater and Houston, 2008), writing (about 'lean thinking'):

"However, before this method is adopted more widely as an environmental technique, the presuppositions of lean thinking should be examined in order to expose boundary judgments that it may impose on research."

The authors discussed the term 'waste', which was shown to encompass an entirely different meaning in lean literature from its meaning in environmental literature. While this difference in interpretation was reasonably explicit, the authors argued that other presuppositions were tacit, and could affect the validity of results derived from a method. They argued that the concept of lean thinking focussed closely on the value stream, a concept that deliberately excluded some categories of stakeholders. This approach was further argued to be inconsistent with systems thinking. Frater and Houston (2008) discussed the distinction between hard and soft systems methodologies, arguing that a combination of hard and soft methods would provide a more holistic and robust approach to an examination of global food supply systems. This argument formed a platform for the proposal in Sect. 4.4.

2.8.5 The relevance of systems thinking to the present study

Several themes develop through the literature of systems thinking. Firstly, the interconnectedness of everything has a sound scientific basis (Bohm, 1980), so that interconnectedness constitutes a reasonable assumption on which to develop subsequent scientific arguments. Secondly, systems thinking views scientific examination of complex systems (represented in my study by the LCA methodology) as a valid tool for understanding the components of a system, but an inadequate tool for predicting the emergent characteristics of a system. The distinction between hard and soft systems is another critical issue. Once it is acknowledged that sustainability issues have characteristics that belong to both hard and soft systems, it follows that the practitioner is required to adopt tools from both disciplines.

A core premise of the present study is that value-rich boundary judgments, both explicit and tacit, are imbedded in sustainability indicators and the methods used to generate them. This premise is supported by key contributors to systems thinking, who are, in turn supported by the philosophers of science.

Chapter Three - Methodology

3.1 Introduction to methodology

3.1.1 Scope definition

A primary objective of this study (Sect. 1.1) was to measure and report energy inputs throughout the New Zealand apple production supply chain. The objective was framed primarily from a New Zealand industry perspective, but in sustainability literature this objective is viewed as encompassing a wider spectrum of issues belonging to the field of global food supply.

A wide range of academic disciples and external agencies has engaged with the issues and debate surrounding global food supply (see Sect. 2.1). It was apparent that in order to achieve a rigorous overview of this subject, I would have to consider an extensive range of academic viewpoints. A broad methodological approach was identified, whereby scientific observation was undertaken following precedents in the field. A concurrent study was undertaken at a self-critical level, whereby the process of the study was examined from the perspectives of the social science and humanities disciplines that were seen to be engaging in parallel debates. That analysis drew on disciplines from the philosophy of science, through to ethics, sociology and systems thinking. In some instances (for example the study of embodied energy in packaging, Sects. 4.2.10, 4.2.3, 4.3), the implications of the self-critical study led to material changes in the indicators reported, but in the main a scientific method was adopted that followed existing research precedents.   The methodological challenge for the scientific study was to identify an approach that would provide an holistic view of an entire industry at a broad-brush level.

The study objectives were stated in terms of an energy analysis of an industry rather than a product. However, the outputs of the New Zealand apple industry are limited to a relatively narrow range of (mainly fresh) food products. Early goals negotiated with the primary sponsor of the research (Pipfruit New Zealand) suggested that sustainability indicators reported as a function of crop yields would increase understanding of the New Zealand apple industry, and help it progress towards

sustainability objectives. So, while the objectives are stated in terms of the industry as a whole, many of the specific results are reported in terms of benchmark energy indicators, allocated per unit of product (or in some instances land area). A comparison of two studies, a dairy industry study (Wells, 2001) and a more intensive study of a small section of the New Zealand apple production industry (Mila` i Canals, 2003) provided early methodological direction.

3.1.2 Physical boundaries, and sub-boundaries of the process

A true end point of the wider study would arguably be the supermarket shelf in the destination country, or even the place of consumption and waste disposal, however the final stages of onshore food delivery have received substantial attention (Jones, 2002, Rizet *et al.*, 2008, Stadig, 2001). It was judged that further data gathering at the broad-brush level would not contribute significantly to this body of knowledge, so the onshore market end component of the study was limited to literature review. The end point of the experimental component of the study was therefore identified as the destination port.

Agricultural research recognises a generic division between pre-harvest (farm-based) processes, and post-harvest processes. The farm gate is widely used as an end point or starting point for agricultural process studies (Barber, 2004a), and this norm was adopted in my study. The farm gate is the arbitrary end point of the farm study, and beginning point of the post-harvest study. Energy inputs incurred by farm workers, such as food and travel, were excluded from this study.

3.1.2.1 Orchard production sub-types

The study distinguished between organic fruit production (OFP) and integrated fruit production (IFP)[14] as well as conventional and intensive growing systems. The top-down method was found to accurately segregate OFP from IFP, as the individual orchards surveyed adhered to one or the other production system. However, intensive growing blocks were invariably part of larger conventional blocks, so orchards were reported as 'intensive' if an arbitrary 40% or more of the planted area was classified

---

[14] IFP has been superseded (since 2006) by Pipfruit New Zealand's "PipSafe" and PipSure programmes.

intensive by the grower. This value was selected after an initial analysis of the results.
One factor that influenced this value was the need to achieve a sample size that would
provide a useful comparison with the OFP responses.

3.1.3 Examining precedents for methodological direction

An examination of the Wells (2001) dairy farm study revealed that while it had
aspects in common with ecological footprint and LCA methodologies, it didn't
conform rigidly to either of these. However, as the research progressed it became
increasingly obvious that LCA has emerged as the dominant model of environmental
sustainability research (Sect. 2.5), and that even if the research was not envisaged as
an LCA study, it would be viewed and reported in that context. This viewpoint may
have been obvious to those working in the life cycle field, but from my personal
perspective the dominance of LCA has crystallised further during the period of the
research. Where energy usage alone was the subject of considerable attention in the
period following the mid -1970s oil crisis, more recent LCA studies report energy
usage alongside emissions, or utilise energy data to predict emissions (Corbett and
Koehler, 2003). Discussions of methodological approaches to energy studies focus on
two alternative methodologies:
- a top-down macroeconomic approach, utilising input-output analysis of sectoral
economic data (Arrous, 2000, Cruz, 2002, Lenzen, 2002)
- a bottom-up process approach regarded by Lenzen (2002) as the traditional, or
normal LCA approach.

A significant area of research has focussed on reconciling these two approaches, such
as a hybrid approach (Nielsen and Weidema, 2001). A criticism of the process
approach made by Lenzen (2001) was that the construction of boundaries invariably
truncates input data by as much as 50%, due to the web of systemic influences lying
outside the boundaries. That author regarded the use of input-output data as more
inclusive, reducing the inherent truncation error of the process approach.
Notwithstanding the emergence of the LCA model, a bottom-up process LCA of an
entire industry was judged to require more resources than were available to this study.
Lenzen (2002) clarified the expression 'bottom-up' by defining orders and a tiered
LCA methodology. In my study middle order analyses were preferred to the detailed

data gathering required for low order, bottom-up studies. A low order, bottom-up process methodology would have restricted the sample size of the farm level study. It was also judged that high order, economic analyses would fail to engage with farm and post-harvest processes sufficiently to inform strategic directions for energy use reduction.

An ancillary approach is the case study approach, adopted by Milà i Canals (2003) and by Barber (2004a). This approach enabled researchers to adopt a process approach, and by inference extend their findings to the wider relevant industry. Barber (2004a) offered his results as benchmarks for the industry while Milà i Canals (2003) avoided claiming that his results constituted industry benchmarks, but offered conclusions in the context of the LCA methodology. From a philosophy of science perspective, the extension of case study results to industry benchmarks falls into the strategy proposed by Popper (1972) of offering an inadequate or incomplete scientific result as a basis for future criticism or refutation.

The modelling approach, where a representative model is constructed based on data from observations (such as case studies) is useful in that the model parameters are explicit, and can readily be manipulated in further research. The construction of virtual farm models is widely used in New Zealand to assist farmers to plan effectively (MAF, 2007). A modelling approach was adopted in my study where gathering data across the sample group was problematic (e.g. an irrigation model App. IV, p231), or where it was judged to offer more representative results than were available from a sample group (e.g. components of the shipping study, Sect. 4.2.6).

The Wells (2001) approach can be considered a pragmatic approach, in that it gathered mid-level industry data from a wide sample group[15]. While this was not entirely consistent with an LCA process approach that would ideally have gathered more detailed data at a lower process level, it could be considered a downward-looking approach at the farm level. That is, a top-down investigation was applied from a mid-level tier. This approach was selected for the farm component of the

---

[15] See Sect. 2.4.1 for a description of the Wells (2001) methodology.

industry study, and is argued to be consistent with the tiered approach described by Lenzen (2002). No single approach was found to be suitable for the various components of the post-harvest study, so all of the above strategies were adopted at various points, with the overall structure being the case study method.

3.1.4 Comparison of top-down and bottom-up methods

A typical bottom-up methodology might be based on the resource requirements and emissions of a single orchard unit, such as a growing hectare, or a metre of tree row (Lenzen, 2002, p1). It is argued that the distinction between 'bottom-up' and 'top-down' is arbitrary, as there is no real limit to the downward scale at which a process can be measured, just as there is no upward limit at which a top-down investigation should be executed. While the direction of viewing a process can be defined (i.e. 'downward-looking' or 'upward-looking') the 'top' and 'bottom' boundaries are constructed rather than real.

Thus, orchard direct energy consumption was measured from totals recorded for the main segments of the growing season (i.e. spring, summer, autumn, winter). These were recorded after the event, and so take on a 'backward-looking' or 'top-down' stance. If fuel consumption had been generated from known fuel consumption data in a predictive sense, it would take on a 'forward-looking' or 'bottom-up' stance.

In retrospect, the farm level top-down methodology provided a high level of confidence with respect to precision and inclusivity of major direct energy inputs. A weakness was that it failed to provide detail about the energy consumption of specific processes.

The process methodology adopted by Milà i Canals (2003) provided significantly more understanding at the process level than the approach adopted in my study, but lost authority when extrapolated to the farm level, and was arguably inadequate for industry level emissions calculations.   The level of detail in the inventory observations of Milà i Canals (2003) was appropriate for his case study approach, but was judged to be prohibitively difficult at the industry level in my study. The approach of Wells (2001) was confirmed as more suitable for my study. A further

advantage of adopting a top-down approach for the farm level study, was that this approach would provide a complementary viewpoint to that of Milà i Canals (2003), providing the multi-scale viewpoint recommended by Giampietro (2004).

Corbett and Koehler (2003) reported a dichotomy between input-output and process approaches with respect to the shipping emission studies. These authors claimed that improved methods were leading to a resolution of differences in reported emissions between the methods. The dichotomy reported by these authors, and by Lenzen (2002), focused on the distinction between the macro-economic input-output approach, and the process approach. However it would appear that the real distinction was not based on scale[16] or tier level, but on the direction of viewing from arbitrarily selected boundaries. The term 'hybrid' can arguably be used to describe any study that combines 'upward-looking' and 'downward-looking' process data.

3.1.5 Issues arising from boundary definitions in energy components

Where possible, in the present research, the boundaries for the various methods adopted over the range of components were constructed so that useful comparisons could be made of those components. However it can be demonstrated that for many components, the nature of the methods adopted to measure energy usage resulted in boundary definitions that were specific to those components, and would acquire a different meaning if applied to a different component.

A tenet of the LCA approach is a 'cradle-to-grave' viewpoint (Wenzel *et al.*, 1997) including the consideration of the end-of-life treatment of products and process components. The methodology of Pimentel (1980), adopted in my study for capital energy components, excluded end-of-life energy costs and emissions, while boundaries were defined for other components that fell short of LCA criteria (as defined in ISO 14040).

Fig. 3.1 shows a representation of uncertainty trends associated with different components of energy. Direct electricity usage in the present study was observed as metered site usage. The packing shed electricity meter constituted a convenient but

---

[16] Issues of scale in agricultural energy studies were examined closely by Giampietro (1994, 2004).

arbitrary sampling point. If a boundary were constructed after electricity generation, then losses incurred in transmission and distribution would be attributed to the product. However, energy use would arguably be greatest if measured as the potential energy of the water held in storage for hydro-electricity and least if measured as useful energy (light or work) available to the plant (Cleland, 2005). The cradle-to-grave LCA approach could account for the energy costs and emissions incurred in the construction of the hydro plant, however accounting for loss of habitat or aesthetic values during flooding would remain problematic. The question that impacted on the present study was "where should boundaries be constructed in order that the contributions of diverse energy components be meaningfully compared or aggregated?"

Studies such as the Wells (2001) report followed the pattern of earlier energy studies in defining narrower boundaries than contemporaneous LCA studies (Lenzen, 1999). End-of-life components could be assumed to be integrated into indicators sourced from recent LCA studies, including for example the values adopted herein for HGV transport. This issue is an example of changes ensuing from rapid evolution of a frame of reference; changes that are imbedded in indicators in the form of tacit knowledge (Sect. 4.3). In this case the changes reflect the emergence of LCA as the dominant analytical framework, and the transition from an energy crisis viewpoint to an ecological crisis viewpoint.

Systemic upstream and downstream environmental costs and benefits have been excluded from energy studies, and only partially included in LCA studies (Fig. 1). Every energy component in this study presented a similar, but uniquely different pattern, in which energy usage was sampled at arbitrary points in more or less continuous energy flows. The sampling point was not always coincident with the study boundary. For example, fuel usage energy values reflected a range of analytical methods, invariably incorporating the calorific value of the substrate as a base component and including various other life cycle components such as extraction and transport. So where Barber (2009) reported values for marine bunker fuel in New Zealand ranging from 42.93 MJ kg^{-1} to 51.23 MJ kg^{-1} it can be seen that these values were derived from a continuum with reported calorific values forming an approximate

base level. The higher value had a higher level of uncertainty (Fig. 1), and the reported accuracy to two decimal places served only to recognise previously reported values. Both fuel and electricity were measured herein at the physical farm boundary, but these energy sources were delivered to that point by supply chains that were region-specific, or even site-specific. Although both fuel and electricity were observed at points consistent with the physical farm boundary, electricity measurements took the form of raw energy values (kWh), while fuel was measured in mass terms. Fuel mass was subsequently converted to energy with values that effectively extended the boundary back into the supply chain.

The overall methodology took account of both direct and indirect energy consumption. However, the indirect components (agrichemical and fertiliser) themselves incorporated direct and indirect energy components. This never-ending chain of dependencies can be argued to result in an interrelated system, where every part is linked in some way to every other part. Hence the dynamic system model (Hjorth and Bagheri, 2006) would provide an improved representation of those interactions, losing however the facility to empirically compare contributions.

A challenge identified in the present research was to attempt to align boundaries and contributions that under close examination could be seen to have incompatible assumptions. The difficulty can clearly be seen in the shipping component. In the shipping study, a base value was derived from a reported fuel use value that was then adjusted by a factor reported by Lenzen (1999) to take account of indirect energy costs. That author later reported systemic inputs lying outside a typical process analysis (Lenzen, 2001), so the reported shipping values might consider factors lying further into the 'high and uncertain' sector of Fig. 1 than other components of this report. The shipping energy value could have been reported as a raw value that only accounted for calorific energy, but was actually reported as a more complete value incorporating a range of unknown assumptions (untested in the context of shipping New Zealand apples).

Energy inputs	Components	High certainty		Low certainty	
				Positivistic systemic ramifications	Normativistic systemic ramifications
		Typical LCA scope – extending partially, but not fully into "Positivistic systemic ramifications".			
		Typical pre-LCA energy study scope			
Direct	Fuel	Calorific value	Extraction costs	Infrastructure costs	Social consequences
	Electricity	Demand side consumption	Supply side generation and transmission	Environmental and human sustenance consequences (negative and positive)	Political consequences
Indirect	Agrichemicals	Calorific value	Manufacture and packaging		Ethical considerations ("is" and "ought")
	Fertiliser	Calorific value	Extraction and manufacture	Carbon sequestration and soil conservation costs and benefits	
	Capital	Production of raw materials	Construction, manufacture and maintenance		Enviro-ethical considerations
	Packaging	Calorific value	Manufacture Biomass cost / benefit		
	Transport	Fuel	Manufacture and maintenance		

Usage, end of life and disposal - environmental costs

Figure 1: Trends in certainty for energy components. Each component has associated impacts that vary from measurable input costs (e.g. substance and energy) through moderately predictable environmental costs to highly uncertain systemic ramifications.

An anomaly can be seen (Fig. 1) in that while the area of uncertainty (taking account of systemic ramifications) could be assumed to be more inclusive, and therefore larger in terms of absolute values reported, this outcome was not necessarily true. The dynamic interconnectivity of systems might result in a change in meaning of reported indicators that could result in lower reported values from more inclusive data. For example, if normativistic influences were included, they might change the allocation and attribution of energy and emissions.

3.2 Farm level investigation methodology

3.2.1 Summary of the farm study methodology

The method adopted for the farm level study was a voluntary census survey of registered New Zealand apple growers (App. VII, p255). The farm survey response (3%) provided an appropriate sample of farm level energy data. It compared favourably with the Wells (2001) dairy industry sample (1%). The dairy study originally comprised a smaller group, but was supplemented to meet a target for irrigated farms. The present study was not enlarged from the original responses, but further information was sought from a sub-group of the original respondents who had indicated in the earlier survey that they would be prepared to co-operate further. This was achieved by means of a supplementary survey and personal interviews.

Following the Wells (2001) methodology, the study sought to measure both direct and indirect energy usage. Wells (2001) made a further distinction between indirect and capital energy. This distinction was adopted at the farm level in my study[17], but was not appropriate for the post-harvest study. Where energy components were identified for which data were already gathered by the industry (specifically farm agrichemical diaries), these were made available by the industry sponsor. Permission was requested of survey respondents for access to electrical energy records from energy suppliers.

The census survey methodology was used to gather data on major capital equipment (eg tractors), but was considered inappropriate for capital items such as post and wire

---

[17] The farm study required energy in agrichemicals to be distinguished from energy in plant.

structures, buildings, pumps and irrigation systems. A modelling method was selected (App. IV, p231). The farm study comprised a measurement of energy inputs into apple production up to the orchard gate. The boundaries for direct inputs were the physical boundaries of the apple orchards surveyed, although indirect energy inputs outside those boundaries attributable to the manufacture and distribution of agrichemicals, fertiliser and capital equipment were calculated.

A general procedure for partial data sets was adopted, where the (per hectare) mean of data provided was applied to data sets in which sections of data were not provided. In the cases (6/36) where the orchard area was not provided, that area was estimated from the mean apple production data.

Reported secondary crops (mostly stonefruit) resulted in an uncertainty, as the direct inputs and capital inputs were attributable to all crops, but the indirect inputs were generally specific to apples. The values were adjusted on a case by case basis with the general assumption of 1 kg of other crops being equivalent to 1 kg of apples. Production was requested (and in most instances reported) in gross tray carton equivalents (TCEs) or kilograms. For the orchards that identified their production as export TCEs, a packout of 65% was assumed[18].

The energy indicators used in this study followed the terminology of Fluck and Baird (1980) - generally adopted in later studies (Barber, 2004a, Wells, 2001). The term energy intensity has been used fairly loosely in literature to describe energy usage against a range of parameters, including both units of product and (in agricultural studies) units of land area. Rather than using an alternative term, in this study the term energy intensity was qualified as "energy intensity (crop)" or "energy intensity (area)".

3.2.2 Direct inputs

The orchard survey (App. VII, p255) requested orchard diesel, petrol and fuel gas records. Growers were asked to indicate whether the records submitted were actual records or estimates. All 36 respondents submitted fuel data. Electricity records (14)

---

[18] The 65% packout value was derived from personal communication with packhouse managers.

were either submitted directly, or requested from the service provider with the grower's permission.

Lubricant usage was derived from machinery inventories (App. I, p215). When the lubricant values were extrapolated on a per hectare basis, there was a large variation evident (9 litres ha^{-1} for two larger operations, and 49, 99 and 104 litres ha^{-1} respectively for three small operations).   The mean value (40) was a factor of four times larger than that achieved by the larger operations. However, when consumption was calculated as a ratio against fuel usage, although a large variation still is evident, the mean (one litre of lubricant to 1443 litres of fuel) is only twice the value of the best practice operations. The ratio of 1:1443 (0.07%) of lubricant to fuel volumes was adopted and fuel energy values were consequently adjusted on a pro rata basis to include lubrication energy.

3.2.3 Indirect inputs

3.2.3.1 Agrichemical energy measurement method

A significant difficulty was identified in the calculation of the embodied energy in agrichemicals. The energy expended in production processes is to a large extent unknown, as chemical companies do not generally divulge their processes, and even if they do, mass and energy flows in large chemical production sites cannot be simply attributed to single products (Geisler *et al.*, 2004). New and evolving chemical groups are particularly uncertain.

Existing methods were considered to be inadequate for a study in which agrichemicals might constitute a significant component. Those methods were based on a few substantial studies of energy inputs for known chemicals, which have then been applied on the basis of function. The implied relationship between embodied energy and function is difficult to support, if not spurious, in view of the variety of innovative chemicals entering the market. A previous New Zealand study (Barber, 2004a) drew extensively on two sources (Green, 1987, Pimentel, 1980). This method assigned energy values based on the function of the chemical (herbicide, fungicide and insectide). Milà i Canals (2003) recognised the limitations of this method for the

modern apple production context, and took some steps towards an improved approach.

A method was developed for the present study whereby the energy content of an agrichemical was estimated on the basis of its molecular structure. The assumption, drawing from Audsley *et al*. (1997), was that the main determinant of the embodied energy would be the primary precursor of the active ingredient in the production process. (Further details of the method are provided in Apps. II, p209, X, CD ROM). This area was identified as an area requiring further research and methodological development, however it is noted that until agrichemical production companies publish their own energy and emission data, and allow it to be verified, uncertainties will remain.

Part of the quality assurance system overseen at the industry level in New Zealand is comprehensive audited records of all pesticides and herbicides and other agrichemicals applied to the growing environment. The industry sponsor provided records for farms that had responded to the energy survey. Not all of these were usable, and not all of the responding farms identified themselves, or gave permission for further research to be conducted. A sub-sample of 19 growers was adopted. The method of data collection can be regarded as a 'top-down' method. However, the distinction is somewhat semantic, as the calculation of energy required me to consider the formulation of individual products and the properties of specific chemicals at the molecular level, more consistent with a 'bottom-up' method.

3.2.3.2 Fertiliser

Fertiliser input data was provided by 9 growers. Fertiliser data was requested in the initial survey. A large proportion of responses left this portion blank, resulting in uncertainty as to whether these were nil responses, or that the growers were unable or unwilling to supply the information. To provide more robust results, the returns were supplemented from survey returns that indicated willingness to participate in further studies, and were in the middle to upper range in terms of planted area, representing a range of soil types. The inclusion of two large orchards (HB1, HB2) on light Takapau silt loam soils provided input from growers who applied fertiliser on an annual basis,

as opposed to the less frequent applications reported anecdotally by growers on the heavier Hastings and Twyford silt loams (Griffiths, 1997).

The energy content of fertilisers has been well documented (Mudahar and Hignett, 1987), and although the sample group was relatively small, there was less uncertainty with respect to the energy coefficients than for pesticides (App. I, p215). The sample group was still larger than that in the case studies measured by Milà i Canals (2003).

The use of urea had been identified in an earlier energy study (Poe, 2003) as a significant variable in orchard energy inputs. Urea usage was surveyed separately from other fertilisers in the primary survey. All respondents provided data.

3.2.4 Capital inputs

Following Wells (2001) the indirect energy content of farm plant, machinery and equipment was distinguished from the energy of chemicals and fertiliser through use of the term 'capital energy'. The energy attributed to these inputs had a relatively high level of uncertainty, even though the subject has been well documented (Pimentel, 1980). Uncertainty stemmed from variability in processes of manufacture and maintenance of machines, and variability in the effective service life of machines. The energy content was calculated according to the methodology detailed by Pimentel (1980).

Eight orchards provided data, so this part of the study took the form of a case study approach (App. I, p215; App X, 'Orchard energy summary', CD ROM). The number and size of tractors used by apple growers relates to fundamental orchard processes. Notes on the calculation of tractor mass are included in App. I, p215.

3.2.4.1 Irrigation and frost protection model

Capital input areas that were not surveyed (irrigation equipment, buildings and support structures) were calculated separately through the development of a model orchard (App. IV, p231).

Wind-machines (used for frost protection) were treated as class two capital items (App. I, p215), along with tractors and pumping equipment (Pimentel 1980). This calculation used a working life of 12 years, which arguably resulted in an overestimation of the energy contribution of wind machines. Wind machines contributed approximately 2% to the total industry capital energy contribution. Of the eight orchards that provided complete inventories of plant, four reported installed wind-machines. This proportion (50%) was almost certainly over-representative of the actual distribution of wind machines on New Zealand orchards in the survey period, indicating a need for further research.

3.2.5 Uncertainties in the farm level study

The top-down methodology resulted in an uncertainty with respect to contractors. The use of contractors was acknowledged in the survey design, and appropriate questions were included. The survey respondents almost without exception reported only the use of contract human labour, which was excluded from this report at the boundary definition stage. A further permutation of this uncertainty could have occurred when farms contracted out their machinery. Since neither of these scenarios was reported, it was assumed that the net result was not significant. Only one respondent indicated that they employed a contractor (to mulch pruning slash). The known areas that were not represented in the survey data were hedge cutting and redevelopment contractors (cultivating, hole ramming, and planting contractors). These recognised gaps, plus other occasional contractors represented an uncertainty in the total energy usage.

A further uncertainty ensued from the arbitrary 40% (of intensive planted area) cut-off selected for categorising an orchard as intensive. A limitation of the top-down methodology was that the energy inputs for the intensive section of the selected orchards were not able to be separated from the conventional inputs. This resulted in a dampening or dilution effect for observable trends in intensive orchards.

3.2.6 Reliability commentary

The following estimates are based on the characteristics of the data and the sample groups. The descriptive statistics for various data categories are presented in App. III, p225.

Fuel Inputs (± 2%)   The values offered for fuel usage can be regarded as robust, in that they were based on both recorded and estimated values from the entire survey sample group.

Electrical Inputs (± 10%)   These values were also based on accurate records, but from a relatively small sample group.

Agrichemicals (±3%)The values reported for agrichemicals are argued to be robust within the constraints of the assumptions for individual energy co-efficients of specific products. The orchards measured represented all the major growing districts in New Zealand, and also represented both OFP and IFP production regimes. High-density (intensive) production systems are also represented in the sample group.

Fertilisers (±10%)   Energy values for fertilisers have been well documented, but the sample size was relatively small in comparison to other data in this survey. The uncertainty lies in the confidence of extrapolation to an industry benchmark.

Urea (±1%)   The values provided for urea were robust, in that all the survey respondents provided data, and the energy content of urea is well documented.

Capital Inputs (±15%)   The energy content of capital inputs was the area of this study with the highest levels of uncertainty. The estimates for wind-machines and bores did not fit well with the assumptions of the Pimentel (1980) methodology, and represented an uncertainty.   The uncertainty here lay in the boundary choices and assumptions rather than extrapolation to benchmark status.

3.3 Post-harvest methodology

3.3.1 Overview of post-harvest methodology

The post-harvest section of this study presented several methodological difficulties. The main components were considered to be direct and indirect inputs into:

Transport:

-road transport from orchard to processing plant, and processing plant to port

-shipping transport from local to overseas ports

-internal transport in and around processing plant

Packing processes:

-energy consumed in the usage, manufacture and maintenance of packing facility plant

Refrigeration:

-energy consumed in initial cooling, and maintenance of chilled temperatures throughout the post-harvest value chain

-energy consumed in the manufacture and construction of coolstore facilities

Packaging:

-energy embodied in apple packaging materials

An area that is acknowledged to be an input in post-harvest energy consumption, but which was not measured in the present study is the use of various treatments such as calcium drenches, plus chemicals consumed in emerging storage technologies. Refrigerant gas emissions were measured in a separate study of GHG emissions from post-harvest facilities in the kiwifruit industry. This study was conducted by the author through New Zealand Ministry of Agriculture and Forestry (MAF) for DEFRA (App. VIII, p261).

A tenet of the LCA approach is the consideration of the end-of-life treatment of products and process components. The methodology of Pimentel (1980), adopted in my study for capital energy components, excluded end-of-life energy costs and emissions. The direct electricity usage accounted only for the metered usage at the sites. Fuel usage energy values reflected a range of analytical methods, based on the calorific value, but including various other life cycle components including extraction and transport. Other indirect components were derived from reported energy values

for which the assumptions were not specific, but it was assumed that older reported agrichemical and fertiliser values took less account of end-of-life plant emissions than more recent studies might. Where a range of values have been reported, a general approach was taken of selecting values that had been adopted in previous studies of a similar nature, usually resulting in a lower rather than higher option being selected.

This issue is an example of changes in the tacit knowledge imbedded in indicators, ensuing from rapid evolution of the frame of reference, in this case the emergence of LCA as the dominant analytical framework. Hence studies such as the Wells (2001) report have followed the pattern of earlier energy studies in defining narrower boundaries than recent LCA studies while end-of-life components could be assumed to be integrated into indicators sourced from LCA studies, e.g. Lenzen (1999).

3.3.1.2 Methodological difficulties in the post-harvest energy study

The first difficulty encountered was an artefact of the evolution of the New Zealand apple industry. That is, the regulated single desk model of marketing (finally revoked in 2001) had led to substantial centralised coolstore assets in the main growing districts (McKenna *et al.*, 2001, McKenna *et al.*, 1998, McKenna *et al.*, 1999). Early discussions with the organisations managing these stores in the deregulated environment indicated that it would be difficult if not impossible to allocate energy costs to individual products passing through these large stores. The reason given was that the plant and energy inputs were centralised, the cooling plant servicing a variety of stores processing a range of products, including not only apples but other fresh fruit, produce and even manufactured food goods. Whatever the facts were, the indication was that the organisations did not perceive themselves as being able to contribute usefully to the research.

A different research strategy was indicated. The remaining options identified were a modelling approach or a case study approach. A decision was made to pursue the case study approach, if organisations could be identified that met specific criteria. Those criteria were:

- The organisation(s) had to represent a vertical slice of the post-harvest value chain, by owning or managing a discrete volume of fruit from the orchard gate through to the point of export (the shipping port).

- The organisation(s) had to manage sufficient volume of fruit to reasonably represent a sample of the entire industry.

- The organisation(s) had to be sited in major growing districts to reflect the conditions under which the majority of the industry operated.

Some organisations that were approached felt that their processes were too complex to be able to be isolated and allocated. This reservation was interpreted as meaning that a substantial proportion of their crop passed through centralised coolstore facilities.

Two organisations that met the stated criteria and were willing to support the research proposal (case study one, CS-1; and two, CS-2) were identified in consultation with Pipfruit New Zealand. A third potential case study subject met the first two criteria, but not the last. It was sited in a minor growing district, not represented by any responses in the farm level study, and was consequently rejected.

A similar methodology to the farm level studies was adopted for the case studies. A site-level top-down approach was based on an initial survey (App. IX, p269) personal site visits and interviews with senior managers. The overall approach measured the total energy inputs for each case, and attributed those inputs to the reported product outputs on a seasonal basis. (See Fig. 3.1 for a summary of the methods adopted in the post-harvest study.)

3.3.3 Summary of post-harvest case study methodology

On-site direct energy usage was calculated from fuel and electricity consumption, following a top-down energy measurement approach. For heavy goods vehicle (HGV) land transport, energy usage was estimated from measured and reported distances travelled. A model specific to apples was developed for shipping and reefer containers.

The CS-2 complex utilised an adjacent coolstore (Store 2) via a contractual arrangement with another organisation. The electricity usage for that store was not provided, but was estimated on the basis of equivalence per storage capacity to the measured stores.

Indirect energy consumption for buildings, refrigeration and packing plant, and lift-trucks was calculated from measurements of building area and estimates of machinery mass. (Note that in the post-harvest study 'indirect' and 'capital' energy were both treated under the single categorisation of 'indirect energy'). For HGV transport, indirect energy was assumed to be contained within reported inventory data (Webb, 2004) but for shipping it was applied as an adjustment using values reported by Lenzen (1999). The embodied energy in packaging was estimated (note: the assumptions of previously published data were challenged in this section in an argument that supports the philosophical inquiry in Sect. 3.2.3). Some components (eg shipping) were developed as a generic component of both case studies.

3.3.4 Lift-truck study methodology

The direct energy consumption of lift-trucks was measured through fuel usage and electricity usage. Both case studies reported lift-truck fuel usage, subject to uncertainties, ambiguities and estimates provided by the site managers. Electricity usage for recharging forklift batteries was contained within the total direct energy usage for packhouse-coolstore facilities in both cases, so although electrical energy use for lift-trucks was accounted for in the total energy consumption measured, only fuel usage could be assigned directly to lift-trucks.

Basic information on the number and type of lift-trucks owned and leased by both CS-1 and CS-2 was provided. Additional information regarding the actual life-expectancy of electric lift-truck batteries was derived from personal communication with lift-truck hire companies in Hawke's Bay.

3.3.4.1 Allocation of waxing and lift-truck diesel

Diesel in CS-2 was utilised for both diesel lift-trucks and the heating required for fruit waxing. CS-2 managers reported that fruit waxing was the larger component of diesel

consumption, but the data available did not differentiate between the two. A separate small study of fruit waxing was conducted in a Hawke's Bay packhouse utilising LPG rather than diesel. This study produced values that compared closely with the energy content of the entire diesel usage in CS-2, confirming that a significant proportion of diesel energy should be attributed to the waxing operation. The other factor taken into account was the energy usage that had been reported for LPG forklifts. Diesel usage was allocated in the proportion of waxing : lift-trucks = 2:1, allocating a proportion of the diesel to the lift trucks that was consistent with LPG energy usage, but less than the requirements for waxing Waxing energy was allocated exclusively to export fruit volumes since in CS-2, only export fruit was waxed.

3.3.4.2 Indirect energy allocation for lift-trucks and batteries

An estimate of the indirect energy attributable to the manufacture and maintenance of lift-trucks followed the methodology of Pimentel (1980). Reference values have been provided for manufacturing and recycling a 25-kWh vehicle battery (Gaines and Singh, 1995). Batteries in use in New Zealand packhouse-coolstore situations typically last 8-10 years (personal communication with lift-truck service provider). The authors of an LCA study of Toyota lift-trucks (Toyota, 2001) adopted a useful lifespan of 14 years, but allowed for two battery changes over this time. That study appeared to assume a higher number of machine operating cycles than is typical for the New Zealand situation, my study reflecting the seasonality of the New Zealand industry. The analysis presented in this study was similarly based on a nominal machine life of 14 years. A new battery was assumed to be supplied on purchase, being replaced by one recycled battery during the working life.

3.3.5 The indirect energy content of coolstore buildings and refrigeration plant

The indirect energy content of coolstore buildings used in post-harvest apple production was calculated here as the sum of the embodied energy in an agricultural service building plus the embodied energy in a roof-wall layer of polystyrene, and an under-floor layer of polyurethane foam (based on best practice). The model assumed a storage temperature of 1.5 to 3 degrees C, and exterior conditions ranging from –3 to 30 degrees C during the storage season.

A methodological question considered was whether the indirect energy should reflect the actual coolstore buildings in the case studies, or whether the indirect energy should reflect the requirements of apples. This question arose because several buildings (particularly in CS-1) were significantly over-designed for chilled apple storage. Some of these buildings were leased out from time to time for frozen storage. This flexibility may have been planned at the point of design, but it is likely that the buildings were originally designed for frozen storage, and deployed later for the reduced demands of chilled apple storage. The additional indirect energy (specifically higher insulation rating) over and above the requirements of apples arguably should be attributed to frozen goods that are held in these buildings from time to time.

A decision was made to base the indirect energy component on a simplified model, based on the design requirements for chilled storage. A contributing factor to the decision was the difficulty in accessing design specifications for the buildings, some of which were leased from organisations outside of the companies with which research agreements had been made.   Lastly, since an objective of the wider study was to generate benchmark values, the use of a model based on actual building dimensions, but on modelled construction specifications was justified.

The factors required (Pimentel, 1980) for assessing this component (Table 1) and the insulation materials appropriate for the construction of coolstores meeting the storage specifications defined above (Table 2) resulted in the reported values (Table 3). (The design requirements were derived from a synthesis of commercial product advice, and horticultural advisory websites).

3.3.5.1 Allowance for mechanical refrigeration plant

An estimate of the mass of mechanical plant in a coolstore of 8000 m^3 (based on personal communication with a refrigeration engineer) was 5-8 tonnes, comprising 1.5-2.0 tonnes of copper and 3.5 – 6 tonnes of steel. This proportion of plant mass to building capacity was used in both cases. Refrigeration plant was not included in the machinery classification of Pimentel (1980) however he provided a generic approach for calculating the energy content of mechanical plant, providing estimates for the

fabrication energy of agricultural plant ranging from 6.3 MJ kg^{-1} to 14.6 MJ kg^{-1}. The complexity of refrigeration plant indicated that it should be attributed a higher value in this range. A critical aspect was the value for repairs, allocated as a percentage of original equipment energy cost expended over the useful life. These values ranged from 45% to 93%. The higher values were accorded to equipment such as mowers and fertiliser spreaders, and the low end for two-wheel-drive tractors and stationary

Table 1: Factors for calculating the energy embodied in refrigeration plant

	Steel	Copper
Metal mass (t)	5	1.8
Fabrication MJ kg^{-1} (equivalent to class 6)	13	13
Repair% (equivalent to classes 1 and 5)	75	75

The classes specified are from Pimentel (1980).

Table 2: Coolstore construction materials

	Insulation (RSI mm^{-1})	Insulation – 50mm under-floor (RSI)	Insulation – 100 mm wall (RSI)	Insulation – 150 mm ceiling (RSI)
Polystyrene extruded panel	.033		3.3	4.95
Polyurethane extruded panel	.050	2.5		

RSI is thermal conductivity (R) in square-metre kelvins per watt.

Table 3: Embodied energy in post-harvest buildings

	Energy density	Wall embodied energy (MJ m^{-2})	Ceiling embodied energy (MJ m^{-2})	Floor embodied energy (MJ m^{-2})	Source
Building structure	14.32 MJ m^{-2}				Pimentel (1980)
Polystyrene panel	61-113 MJ m^{-2} RSI^{-1}	201-373	302-559		(Harvey, 2007)
Polyurethane panel	144-196 MJ m^{-2} RSI^{-1}			285-490	(Harvey, 2007)

power units (Pimentel, 1980, p11). The relevant characteristics of the case study refrigeration equipment were that it was stationary, but was vulnerable to damage from moving machinery. The motor and compressor units were in continuous use, and were considered to be subject to relatively high rates of wear.

The CS-1 site had five large refrigeration complexes, totalling 800,000 m^3, while CS-2 had two totalling 40,000 m^3. In both cases, some plant assets (packing, coolstore, CA stores) were owned by organisations other than the organisations with whom research agreements were formed, a factor that restricted the availability of information.

3.3.6 Packing shed equipment

An estimate was made of the total mass of equipment in a packing shed and site, based on the layout described in Frater (1999, p123). Following the approach of Pimentel (1980), the total mass was treated as similar to the material composition of a large combine harvester; that is mainly steel of varying grades and functional complexity, plus some synthetic components. The packhouse equipment was estimated to have a total mass of 13 tonnes, of which 1 to 1.5 tonnes was synthetic compounds. The fabrication energy was treated as equivalent to class 3, and the repairs and maintenance as class 5 (recognising the extent to which equipment may be modified from season to season.) The useful life was 10 yr.

3.4 Packaging

The components of apple packaging considered were:
- wooden pallets
- paperboard box and kraft liners comprising the standard z-pack apple carton, and its derivatives
- moulded trays.

Other minor packaging components (e.g. cornerboards and strapping), and packaging types other than standard z-packs were not considered.

3.4.1 Energy in sawn timber packaging

Boustead and Hancock (1981) calculated a total energy 1106.7 MJ for a pallet weighing 25.4 kg. Their calculation combined the embodied energy with the recoverable fuel energy (the exergy) of the wood. They argued that since biomass in various forms was widely used as a fuel in the pulp and paper industry, that the fuel energy content of the final product should be included in the embodied energy. This treatment was rejected as invalid in the present study (see Sect. 4.2.10, 4.5.).

Boustead and Hancock (1981) reported a value of 17.2 MJ kg^{-1} as the "fuel content" or "feedstock energy" for wood with a moisture content of 12%. This component was subtracted from their total, resulting in a benchmark value of 26.4 MJ kg^{-1} for wooden pallets. Although the transport mix varies from the New Zealand model, and the distances are greater in for European production, the main energy components of "sawing and make up" and softwood production (ex Portugal) can be argued to represent the New Zealand model. Boustead and Hancock (1981) reported 8 MJ kg^{-1} as a representative average energy input for the production of "raw wood from standing timber"[19].

Pallet standards for apples are specified according to the mass and type of fibreboard box they support (Wright *et al.*, 1992) and the energy content for a specific pallet is assumed to be proportionate to the mass. A representative dry New Zealand apple-carton pallet[20] weighed 20 kg.

The New Zealand process included harvesting, milling and kiln drying. A pallet manufacturer expressed the argument that as the timber used for pallet manufacture in his operation was 'downfall' (waste recovery) from a higher-grade timber value stream, and since the energy would be spent anyway to recover higher grades, the energy content assigned to the pallet should be reduced. This argument was rejected, as many primary produce value streams produce a variety of grades of product each valued differently by various customers. Once a product is identified from a waste-

---

[19] This value is a component of the benchmark 26.4 MJ kg^{-1}.
[20] Information provided by pallet manufacturer.

stream, then the raw material is no longer waste, and that product contributes to the economic viability of the process.

A similar situation arose with apples themselves, where the question was posed whether the energy content of exported apples should be divided by the gross crop (including local market and process grades), or the net export crop. The decision in that case was that the energy content should be derived from the gross crop. Local and process[21] markets were regarded as segments of the total market. A similar principle was applied to timber packaging, whereby the energy content of the product was allocated on the basis of mass, irrespective of the relative commercial value of the product. Jungmeier *et al.* (2002) described alternative bases for allocation in a study of wood products (framed within ISO 14041 procedures), including economic and volumetric options as well as mass.

Further differences are acknowledged to exist between the reference models, and the New Zealand context. The Boustead and Hancock (1981) model did not specify (or exclude) kiln drying. In addition, the internal distances involved in New Zealand were relatively small compared to continental production.

3.4.2 Paperboard and pulp packaging

The energy content of packaging is discussed further in Sect. 4.5 where it is explored as an example of tacit knowledge, and hidden assumptions in energy indicators. The following section considers the energy content of wood-fibre packaging with respect to the values adopted in this report.

Energy values for wood pulp and paperboard have been reported to be highly sensitive to boundary decisions and assumptions. Wiegard (2001) found emissions to be sensitive to the amount of recycled material used as feedstock. Selke (1999) explained that the energy content for making paperboard is a function of transportation distances for raw materials, pulping processes used, paperboard machinery, thickness and other variables. She stated:

---

[21] "Process" is the industry term for low-grade apples that are processed to juice.

"the environmental impact of package alternatives is determined more by the basic package material or materials than by the package type or style."

Hence an estimate of the energy content of apple packaging can be derived from the energy content of the mass of the component material. Selke (1999), citing Gaines (1981), offered values ranging from 58.8 MJ kg^{-1} for natural linerboard to 77.6 MJ kg^{-1} for bleached board. However these values also included the combustion energy of the raw material, a practice that is argued to be inappropriate for the present context. To provide an embodied energy benchmark for New Zealand apples, the exergy value of raw feedstock (17.2 MJ kg^{-1}) was deducted[22], resulting in a value of 41.6 MJ kg^{-1} for unbleached paperboard.

New Zealand and Australian timber and pulp operations utilise best practice for both environmental and cost reasons. Paperboard packaging is invariably recycled, but this occurs at the endpoint of the value stream (in Europe for example). Imported, recycled waste material has been reported to have negligible implications for emissions (Wiegard, 2001).

The extent to which the individual case varies was demonstrated in a Swedish LCA report on milk tetra brik production (Rydberg *et al.*, 1995) that reported the production of pulp utilising biomass energy sources resulting in a net energy surplus. However, a negative energy value would require surplus energy from the process to be contributed usefully to the value stream or to the wider system. Potential mechanisms for this include returning surplus electricity generation to the national grid, or generating fuels such as bio-gas or producer gas (EECA, 2007). These opportunities are case specific, and cannot be assumed as part of the New Zealand benchmark. Recycling fibre yielded an energy savings of 46.4 MJ kg^{-1}, and a value of 37.3 MJ kg^{-1} was reported for the production of "corrugating medium with a recycled content of 30%" (Selke, 1999). In her study, 75% of the energy was provided from wood or wood by-products, with the remainder being purchased energy.

---

[22] The "kg for kg" equivalence is an untested assumption.

In a personal communication, a representative of a major Australasian corrugated paperboard manufacturer provided a value of 0.85 kg CO_2 kg^{-1} (derived assuming 0.45 kg CO_2 kWh^{-1}) for a product with kraft liners and recycled medium fluting. A production energy value of 6.8 MJ kg^{-1} was derived from these reported values. A further comparative value of 8.9 MJ kg^{-1} was derived from the primary inputs for a single plant reported by Wiegard (2001, p56)[23]. Weigard excluded the 60% of production energy supplied from biomass fuel.

Weigard, (2001, p138) reported four separate LCA-modelled scenarios, reporting that fossil fuel usage was responsible for 71% of plant carbon emissions. Emissions were sensitive to energy source, the proportion of biomass fuel and the nature of alternative energy sources and the proportion of recycled feedstock. The author didn't specifically report energy usage, and because of the complexity of biomass factors, in paperboard production factors affecting energy usage cannot be assumed to be identical to those influencing carbon emissions. However, it is clear that both energy and carbon emissions in paperboard production are highly case specific, and sensitive to assumptions and boundary choices.

Unresolved variation remained between 37.3 MJ kg^{-1} reported by Selke (1999), 41.6 MJ kg^{-1} derived from the same source, 6.8 MJ kg^{-1} reported by an actual supplier to the New Zealand industry and the primary energy value of 8.9 MJ kg^{-1} derived from Wiegard (2001). An assumption can be made that the two low values would need adjustment upward when delivery transport costs were added. The Selke (1999) value could be argued to be based on outdated data that have since been ameliorated by efficiencies (Wiegard, 2001; EECA, 2007). A realistic benchmark would fall somewhere in between, but closer to the lower values.

An achievable value was estimated to lie between 10 MJ kg^{-1} and 15 MJ kg^{-1} for new or purchased energy inputs into the manufacture of unbleached apple carton paperboard and kraft liners, where at least 60% of the production energy is derived

---

[23] The data were reported for an Australian recycled paperboard plant for 1998-1999.

from waste biomass. The benchmark value attributed to apples in this study was calculated from a value of 12 MJ kg^{-1}.

The influences I took into account when choosing a value closer to the lowest reported value (6.8 MJ kg^{-1}) than the highest value (46.1 MJ) were: the relatively low transport component (due to short land transport distances) for products manufactured and used within New Zealand, the relative efficiency of NZ hydro power systems (Scully, 1998), assumed improvements in manufacturing technology (since the 1980s and 90s) and an assumption that for a product largely composed of wood-derived cellulose, the greatest component of production energy would be the direct energy used in its manufacture. The range of 10 MJ kg^{-1} to 15 MJ kg^{-1} reflects the reported values of 6.8 MJ kg^{-1} and 8.9 MJ kg^{-1} as a range for the direct (purchased) energy baseline, and reflect an assumption that direct energy would comprise 50% to 75% of the total inputs. The single value reported (12 MJ kg^{-1}) is therefore an estimated benchmark to be tested further.

Although low-density pulp apple trays were reported to be manufactured from a high proportion of recycled material, requiring less mechanical processing than paperboard, tray producers did not report the use of biomass energy. A value based on 60% of the paperboard value (7.2 MJ kg^{-1}) was used as an interim benchmark.

3.4.3 Attributing the packaging energy to apples

To arrive at a value for energy and carbon emission values of the packaging component of New Zealand apple exports, the calculations were based on a 56 carton pallet (18.5 kg, five tray carton) carrying 1036 kg of apples.

3.5 Shipping investigation methodology

3.4.1 Overview of shipping methodology

The subject of shipping posed a number of questions and challenges: Should previously reported indicators, e.g. Webb (2004), for shipping freight be accepted as adequate without recourse to further investigation? Do the specific circumstances of

shipping apples from New Zealand to Northern Hemisphere destinations impose constraints or variables that were not accounted in previously reported data?

The scope of the present study did not support gathering new data to confirm or challenge existing shipping studies (see Sect. 2.3.2). However, while reported shipping freight values were useful, two issues required further attention:
- the relative energy inputs of containerised refrigeration and shipping transport energy consumption (as a function of mass and distance)
- the attribution of energy to refrigerated apples.

To resolve these issues, a simplified bottom-up methodology was developed. The methodology required some raw data with respect to containerised vessels. It was found that data for individual vessels was available on various publicly accessible databases. A further set of questions remained unresolved, encompassing issues such as routes and return loadings, and attribution for part loads. All of the values reported herein were based on a one-way direct voyage (a pragmatic methodological choice that, it is acknowledged, does not adequately reflect reality).

I engaged in discussions with major shipping companies who, it was assumed, could have provided much, if not all, of the information sought. However, issues over commercial sensitivity resulted in this avenue being rejected, although indicative values were provided in personal contact. It is assumed that when benchmark indicators derived in the present study are reported, the shipping companies will be able to respond to those indicators if they consider themselves to be unfairly represented, or able to perform better.

3.5.2 Introduction to shipping investigation method

To estimate the energy expended in transporting fruit from New Zealand to destination ports, data was collated from a range (n = 49) of container ships, reported on various websites, some company and some private interest. (For the data spreadsheets see App. X, 'Shipping workbook', CD ROM). The methodological question considered here was, should energy usage be based on actual ships used

(even if ships supplied by shipping companies were less than 'best case'), or should the study be based on a representative sample of appropriate vessels?

Shipping companies have sole discretion over the selection of vessels. From the perspective of New Zealand export logistics, it is challenging enough to secure refrigerated sea freight capacity to match seasonal variation with commitments to customers. Adding an expectation that shipping companies will supply ideal vessels is unrealistic. However, the nature of a benchmark value is that it should be based on appropriate data. Therefore vessels selected represented a cross section of appropriate vessels, acknowledging that the New Zealand apple industry is not an influential actor in global shipping and has limited bargaining power. Even when vessels that were judged from the specifications to be inappropriate were removed from the sample group, considerable variation of vessel size and refrigerated container capacity remained (Fig. 2).

The range of vessels for which data was collated varied from 21,000 DWT to 166,000 DWT, and from maximum payloads of 1552 TEU to 15,200 TEU, and with reefer container capacities from 75 FEU to 1000 FEU. The selection was deliberately biased towards larger more modern vessels as these vessels are designed for longer routes, while smaller vessels are preferred in shorter coastal routes (EPA, 2000).
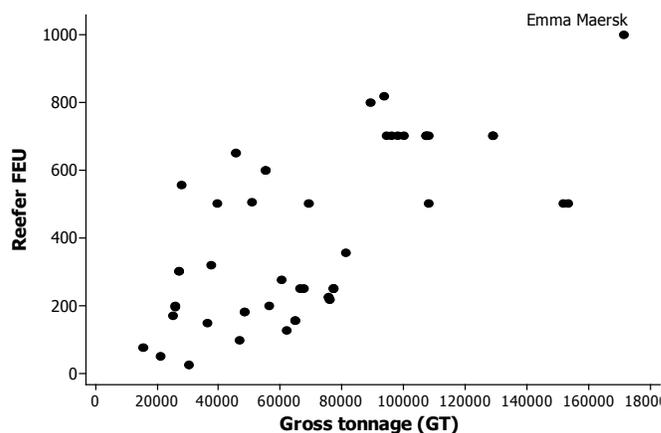
Figure 2: Vessel gross tonnage (GT) versus reefer container capacity (FEU)

Vessel size limits, and is a predictor for, container capacity[24] (Fig. 2). The largest vessel in the sample was the Emma Maersk, representing the new generation of very large vessels. The vessels selected in fact represent a larger pool, as vessels are invariably built as a class with similar specifications. In some cases the number of sister ships was reported (n = 1- 7). However, sister ships also exist within the group of selected vessels. The selection of particular vessels was not an indication that these vessels have been deployed in New Zealand routes. Furthermore, the specifications of the main New Zealand apple export ports may not comply with the requirements of the very large, more recent vessels in the sample group.

3.5.3 Method Development:

- The total energy consumed by a container ship was calculated as the sum of the direct energy and the indirect energy[25]. The direct energy was calculated from the ships' engine outputs, both through calculated fuel consumption and as a more direct function of energy output. A fuel consumption energy calculation based on engine power output has been strongly supported by emissions research (Corbett and Koehler, 2003, EPA, 2000).

- The direct energy attributable to apple freight was calculated as the sum of the energy attributable from normal marine transport, and an additional component for refrigeration.

- A value reported (37.3%) for the proportion of the total energy consumed by coastal shipping (Lenzen, 1999, p21) as an "indirect" component, including construction and maintenance, was used to derive a total energy value from direct energy consumption.

 - The direct energy was calculated as a function of the rated power, cruising speed and payload of the vessel. Fuel consumption was predicted from the rated power. EPA (2000) advised the use a value of 80% of the rated power of a ship for energy expended in cruise mode. Corbett and Koehler (2003, p5) reported a fleet-average fuel consumption rate (marine bunker fuel) of 206 g kWh[-1] for transport ships.

- The vessel refrigerated payload, reported in FEU or TEU, was converted to tonnes of apples based on the capacity of a hi-cube container (Wild, 2008). Wild (2008)

---

[24] Gross tonnage (GT) is a unit-less measure of vessel volume, whereas deadweight (DWT) is a measure of carrying capacity.
[25] Throughout the post-harvest analysis the nomenclature 'indirect energy' was preferred to the term 'capital energy' that was used in the orchard energy study to distinguish substances from plant.

reported a "broad average" value of 3.6 kW TEU^{-1} for integral refrigerated containers. This author described a movement toward integral refrigerated units, and a subsequent decline in porthole refrigeration. The calculations in my study were based exclusively on integral containers. New Zealand apples are transported in mid-range conditions (ie. chilled mode rather than frozen, and through both temperate and tropical regions), so the value of 3.6 kW TEU^{-1} was accepted as reliable.

3.5.3.1 Direct energy usage of non-refrigerated containers

If a vessel contained all non-refrigerated containers the direct energy attributable to each container would be the total direct energy (e_{tdir}) divided by the number of containers (n). That is, since the primary purpose of the voyage is to transport freight, the entire direct energy cost of the voyage could be attributed to the freight.

Direct energy per container $= e_{tdir}\, n^{-1}$ kW TEU^{-1}

Individual vessels have a reefer container capacity significantly less than the total container capacity (the mean of the 50 ships sampled is 13%). The energy attributable to them has two components:
- a transportation component
- a refrigeration component.

The transportation direct energy component (e_{tsp}) of the entire payload, including the refrigerated containers, was calculated as the total direct energy expended less the total direct energy attributable to refrigeration (e_{rf}):

$$e_{tsp} = e_{tdir} - e_{rf}$$

The total energy consumed by a refrigerated container was calculated by summing the transport and refrigeration component, and adding an indirect component (based on the value provided by Lenzen (1999), and where n_{rf} is the number of refrigerated containers in TEU).

$e_{tsp}\, n^{-1} + e_{rf}\, n_{rf}^{-1}$ + (indirect component)

The direct energy value (in kWh TEU^{-1} k^{-1}) was derived by dividing the value e$_{tsp}$ by the vessel's reported cruising speed. To report this value specifically for apples, a conversion to tonnes was based on a typical refrigerated apple load.

3.5.4 Marine bunker fuel

Marine bunker fuel, also classified as "number 6 fuel oil" or "residual oil" or "high sulphur fuel oil" varies in its composition, and hence a range of values are reported for its energy content. Barber (2009) reported values for New Zealand bunker fuel of 42.93 MJ kg^{-1} as a "consumer energy value" and 51.23 MJ kg^{-1} in "primary energy terms". Browne *et al*. (2008) used a value of 43.50 GJ t^{-1} for a food supply chain energy analysis. IEA (2005) have published a gross calorific value of 43.76 GJ t^{-1}, and a net calorific value of 41.47 GJ t^{-1} for high sulphur fuel oil. This last value was adopted in this report.

3.5.5 Uncertainties in sea transport calculations

3.5.5.1   Auxiliary engines

An uncertainty exists with respect to recent large container ships (such as the Emma Maersk) that are reported to have substantial auxiliary engines. In the case of the Emma Maersk, these are reported to total 29,000 kW, compared to the main engine rated power (80,080 kW). This is significantly in excess of the auxiliary power allowance (750 – 1000 kW) recommended by EPA (2000). The proportion of auxiliary power dedicated to refrigeration during normal running is not known. This uncertainty was assumed to be contained within the reported average fuel consumption as a function of the power of the main engines.

The uncertainty around auxiliary engines is based on a variety of normal operational conditions, including:
-    a situation where the refrigeration component is exclusively driven by auxiliary engines, so that the auxiliary engines normally operate at full load

- a situation where the refrigeration component is partially driven by auxiliary engines, and partly by main engines. Here the auxiliary engines also normally operate at full load

- a situation where the auxiliary engines are sized to allow for massive pumping loads in extraordinary conditions (a consequence of modern "hatchless designs"), and for manoeuvring adjacent to ports.   In this situation, most of the auxiliary engines would not be operating under normal transit conditions.

It is reasonable to conclude that despite this uncertainty, the rated power of the main engines is a predictor of fuel consumption for all designs.

3.5.5.2 Vessel speed

Vessel speed was sometimes reported in vessel specifications both as maximum speed and cruising speed, but in most cases only a single value was reported, which was assumed to be cruising speed. Fuel consumption in large vessels was reported to be sensitive to small increases above the optimum cruising speed (EPA, 2000). Cruising speed is typically 2-3 kts below the maximum. This assumption represents a potential under-reporting of energy usage of up to 5% for some vessels.

3.5.5.3 Fuel consumption

Corbett and Koehler (2003) discussed the emissions of vessels operating at loadings less than 80% of rated load. The emissions are reported to be higher for lower loadings. They also reported the loading of auxiliary engines, the power of which was not specified for most of the vessels in the sample group. An assumption is made that the uncertainties implied in the use of auxiliary engines, and in lower engine loadings associated with slow speed, manoeuvring and hoteling operating modes are incorporated within the reported fuel usage value (206 g kWh^{-1}) provided by Corbett and Koehler (2003, p5). This fuel usage value is assumed to be a function of the cruising power expenditure of the main engines (i.e. 80% of the rated power) and the calculations are based on an assumption that a vessel operates at cruise mode for the distance of a trade route.

3.5.6 Indirect component of reefer containers

The indirect energy component derived from the value reported by Lenzen (1999) for general shipping transport was calculated from the total direct energy, so a proportion of this total was attributed to reefer containers. Reefer containers have different indirect characteristics to vessels (less mass in proportion to energy usage, but lower durability), resulting in a further small uncertainty.

3.5.7 Attribution of marine transport energy per kg of apples

TEUs were converted to kilograms of apples using a factor of 10,878 kg TEU[-1] (based on a 40 ft hi-cube container carrying 1176 z-packs in 56 18.5 kg carton pallets. The total payload of such a container is 21,756 kg, or 10,878 kg TEU[-1]). Other packaging types were not calculated, but bin type exports would be heavier, and retail tray types would be lighter. CS-2 used the z-pack format for 78% (2007) and 72% (2006) of their export volume. CS-1 used the z-pack format for 93% of their 2007 exports. (For energy consumption attribution calculation for refrigerated apples see Table 4; App. X, 'Post-harvest workbook', CD ROM).

3.5.8 The prediction of energy usage from basic vessel parameters

This method extended the relationship between basic vessel parameters and resulting energy attribution into a predictive equation through a regression analysis, treating the container vessel analysis as a 'black box', bypassing the adjustments made for apple loads, fuel energy conversions, and refrigerated container energy consumption (Table 5; App. X, 'Shipping workbook', CD ROM).   Following an initial analysis, five unusual observations were removed, and a regression equation was derived from a summary of the remaining 44 observations. The five vessels removed from the original sample comprised two older vessels, and three examples of very modern, large fast state-of-the-art vessels. The age of vessels, even within the last few decades, appeared to have an influence on energy consumption. To test this relationship, the modified sample was ordered by build date, to explore the anticipated improvement trend in vessel performance from older to newer vessels.

3.6   The philosophical and systemic investigation

The methodology for this component of the study was conducted as a literature review, with subsequent analysis of, and application to the scientific studies. An outcome of this investigation was the development of an approach for integrating soft system knowledge into present LCA methodology, thereby reducing ambiguity in assumptions and boundary definition in LCA practice, and particularly interventions resulting from or informed by LCA studies. This proposed addition to LCA methodology was not tested in practice, but its relevance to boundary decisions, and implications for results from the present study were investigated.

3.7 Supplementary investigations

Two supplementary investigations were conducted:

1. An investigation into greenhouse gas (GHG) emissions in kiwifruit packhouses. The kiwifruit industry is characterised by more dispersed post-harvest operations than than the apple industry. A research project measuring GHG emissions (for DEFRA, through MAF – see glossary) was undertaken as a valuable supplementary exercise to the apple energy project. The project (App. VIII, p261) took the form of a survey and personal site visits. .

2. An investigation into the energy content of apple prunings, and potential mechanisms for utilising that energy as a substitute for fossil fuel energy, or as a biochar soil supplement, was conducted (App. V, p239). The methodology for this investigation was a review of biochar and pyrolysis literature.

Table 4: Development of shipping energy consumption calculation

Column	Description	Calculation	Source
G	Rated power (kW)		
AB	Cruising power (kW)	G * 0.8	(EPA, 2000)
F	Reefer FEU		
Y	Maximum TEU		
H	Speed (kts)		
I	Speed (kph)	H * 1.852	
Z	Total refrigeration energy, e_{rf} (kW)	F * 7.2	(Wild, 2008)
AA	Total refrigeration energy, e_{rf} (GJ hr^{-1})	Z * 0.0036	
J	Fuel consumption (t hr^{-1})	AB * 0.000206	(Corbett and Koehler, 2003)
K	Fuel energy content (GJ hr^{-1})	J * 41.47	(IEA, 2005)
L	Total payload direct transport, e_{tsp} (GJ hr^{-1})	K-AA	
P	Direct transport per TEU per hour (GJ TEU^{-1} hr^{-1})	L * Y^{-1}	
Q	Total reefer energy per TEU per hour (GJ TEU^{-1} hr^{-1})	P + 0.0259	
R	Total reefer energy per TEU per kilometre (GJ TEU^{-1} km^{-1})	Q * I^{-1}	
S	Total reefer energy per tonne kilometre (MJ t^{-1} km^{-1})	R * 1000 * 10.878	
T	Indirect reefer energy per tonne kilometre (MJ t^{-1} km^{-1})	S * 0.594	(Lenzen, 1999)
U	Total reefer energy per tonne kilometre (MJ t^{-1} km^{-1})	S + T	

Columns relate to App. X, Shipping workbook.xls, sheet 'Vessel data'.

Table 5: Development of simplified payload energy model

Column	Column description	Calculation	Source
D	Sea route distance (km)		
E	Voyage duration at 22.7 knots	$D (41.2)^{-1} (24)^{-1}$	
H	Total tonnes of fuel consumed	$E * 187.3$	
I	Fuel consumption per TEU (t TEU^{-1})	$H (6146)^{-1}$	
J	Direct energy consumption per TEU (GJ TEU^{-1})	$I * 41.47$ GJ t^{-1}	(IEA, 2005)
K	Direct energy consumption per kg (MJ kg^{-1})	$J (10878)^{-1}$	
L	Indirect energy consumption per kg (MJ kg^{-1})	$K * 0.594$	(Lenzen, 1999)
M	Payload energy intensity (MJ kg^{-1})	$K + L$	

Columns relate to App. X, 'Shipping workbook', sheet 'Payload calculation', CD ROM

Chapter Four - Results and Interpretation

4.1 Apple orchard energy study

4.1.1 Introduction to the farm-level study

The farm level results are reported by region, by production system and by growing system. The two growing systems reported (IFP and OFP) are supported by industry standards, IFP by the recent PipSure and ultra-low residue PipSafe protocols, and OFP by certification standards such as the internationally affiliated BIO-GRO trademark and the Demeter label[26].

In New Zealand apple production parlance, the term 'intensive' is applied to high-density plantings, often utilising varieties grafted to dwarfing rootstocks. Conventional growing systems vary widely according to region and soil type, but are represented by the description presented in the irrigation model (App. IV, p. 231).

The investigation of energy inputs into apple production at the farm level was approached via the census survey methodology described in Sect. 3.1.1, providing benchmark energy indicators (Table 6).

Table 6: Energy indicator definitions

Indicators	Definition
energy intensity ("crop" or "per crop")	energy inputs per unit of crop yield
energy intensity ("area" or "per area")	energy inputs per unit of land area
production intensity	crop yield per unit of land area
energy productivity	inverse of energy intensity (per crop)
energy ratio	energy of input to energy of output

Fluck and Baird (1984)

---

[26] A comprehensive description of New Zealand farm production systems is provided on various pages of the NZ MAF website, and its MAFNET online publications e.g. MAF (2007).

4.1.1.1 Survey responses

Thirty-six responses from the survey (3% of registered NZ apple growers) were considered useable. By variety, almost three quarters of the gross production in the survey group was Braeburn and Royal Gala (Braeburn being twice Royal Gala). Of the remaining varieties Fuji and Pacific Rose (about equal) were dominant, with minor contributions from Cox's Orange (and derivatives), Pacific Beauty, Pacific Queen, Pink Lady, Granny Smith plus small volumes of other minor apple varieties, pears and stonefruit. The relationships between variety and energy usage were not explored further. By region the respondents comprised Canterbury (2) Gisborne 2, Hawke's Bay (21), Waikato (1), Otago (1), Nelson-Marlborough (9).

The orchards varied in size from 0.75 ha to 73 ha. Thirty-two orchards were operated in an integrated fruit production (IFP) regime, while four were organic fruit production (OFP) orchards. The IFP orchards represented a cross section of New Zealand apple growers, ranging from very small enterprises to business units of large enterprises. The four OFP orchards (totalling 63 ha) represented both small and medium-to-large scale enterprises in the Hawke's Bay and Nelson regions. Twenty-five of the growers reported their production systems as being conventional, and eleven reported their systems as being partly or completely intensive. Five growers with more than 40% of their orchards in high-density plantings were selected as representing intensive production systems (see Sects. 3.1.2.1, 3.2.5.)

4.1.1.2 Summary of results

A summary of the results of this investigation (Table 7) reports energy intensity per unit of gross production, and per unit of land area, and a further summary (Table 8) reports values for secondary indicators. Indirect inputs (agrichemicals plus fertiliser including urea) contributed 40% to the energy intensity (per area), with direct inputs (fuel plus electricity) contributing 38% and capital inputs[27] 22%.

---

[27] Indirect inputs into plant and machinery were reported separately as "capital inputs" following Wells (2001).

4.1.1.3 Breakdown of inputs by percentage

Fuel and lubricants were the largest component of the direct inputs (32%), while agrichemicals contributed 21% and fertiliser (excluding urea) 16% to indirect inputs. The urea contribution (3%) came from about half of the sample group (Fig. 3). The direct inputs, and indirect inputs from fuel and agrichemicals were consistent with previous research, but the 22% assigned to capital equipment had not been specifically identified in prior research. The assumptions associated with this result,

Table 7: Energy intensity summary

Energy intensity (per area) GJ ha^{-1} [energy intensity (per crop) MJ kg^{-1}]				
Total farm energy intensity 54.7 [1.39]	Indirect 33.4 [0.85]	Indirect (substances) 21.6 [0.55]	Fertiliser 10.2 [0.26]	Mineral and organic 8.6 [0.22]
				Urea 1.6 [0.04]
			Agrichemicals 11.4 [0.29]	
		Indirect (capital) 11.8 [0.30]		
	Direct 21.3 [0.54]	Fuel 17.9 [0.46]		
		Electricity 3.3 [0.019]		

Table 8: Secondary indicators

Indicator	Value
Energy ratio	1.7
Energy productivity (kg MJ^{-1})	0.72

The calorific energy value for raw apples[28] was 2.37 MJ kg^{-1}. Energy ratio is the ratio of outputs to inputs, and energy productivity is the inverse of energy intensity.

---

[28] Web ref. http://www.unu.edu , retrieved 30-2-06.
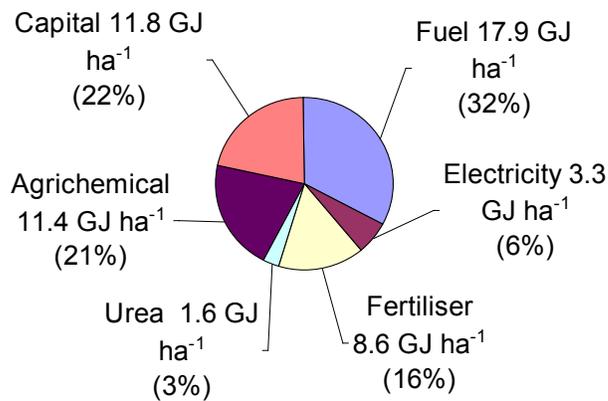
Figure 3: Overall contributions to farm level energy intensity (per area)

particularly those of the useful life of equipment, following Pimentel (1980), require further examination in the context of New Zealand practice. Extremes in the variation of production intensity (Fig. 4) were generally site specific. While the low observations were readily explained by crop failures through weather events, or orchards in redevelopment phase, the high observations were less readily explained. Those observations relate to small blocks, and may simply reflect variations that would occur locally within larger blocks, or reporting errors (e.g. failing to include headlands in reported area).
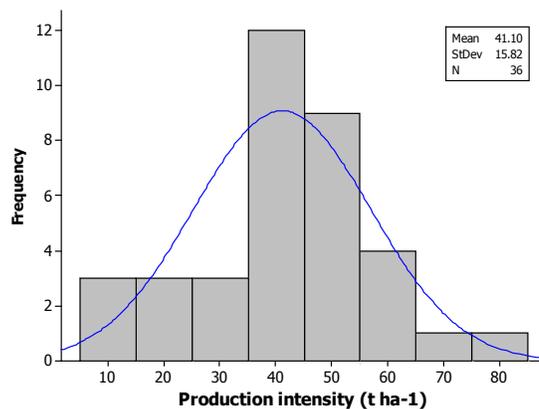
Figure 4: Production intensity frequency distribution (t ha^{-1})

The mean (41.1) can be compared to the higher value (70 t ha-1) on which Palmer and Dryden (2006) calculated their mineral extraction rates. The distribution (Fig. 4) is accepted as normal at a confidence level of 95% (App. III, p225).

The distribution of production intensity by orchard size (Fig. 5) did not demonstrate a significant difference between the conventional and intensive blocks sampled, or the IFP and OFP blocks. A prior Washington State study (Poe, 2003) found OFP

orchards to be less productive. However a comparison of New Zealand organic and conventional farms, including apples, assumed equal (gross) production for both types of regime (Condron *et al.*, 2000). A significant issue reported informally by the OFP growers in my study was meeting customer quality specifications (particularly those defined in biosecurity terms), so for OFP to achieve equal net production to IFP required skilful management.

It would be reasonable to expect intensive orchards to be more productive. The purpose of these growing systems is either to achieve higher production intensities, or to achieve comparable production with lower inputs. The term 'intensive' in agriculture is generically applied to systems that achieve greater yields per production area, invariably resulting in higher energy intensity. These outcomes were not evident in the orchard investigation. If these are not the outcomes, or are not the objectives of high-density plantings, then the term 'intensive' is a misnomer.   If intensive production were to achieve higher yields, proportionally higher mineral inputs would be required, resulting in additional energy requirements. Mineral extraction rates in New Zealand apple production have been reported as (Palmer and Dryden, 2006): 82 kg ha^{-1} potassium, 31 kg ha^{-1} Nitrogen, 7 kg ha^{-1} phosphorus and 4 kg ha^{-1} calcium and magnesium. These rates were calculated for a production intensity of 70 t ha^{-1}. Mineral extraction is a function of crop volume, not land area. Indirect inputs for intensive orchards were grouped in the lower range, however a relatively small sub-
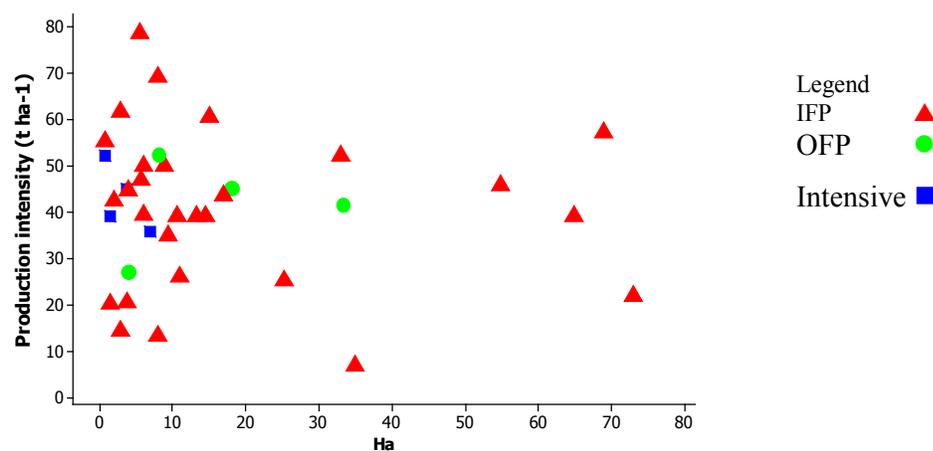
Figure 5: Production intensity (t ha^{-1}) by orchard size

(Range 6.9-78.6, gross mean 39.5 t ha^{-1}.) The term 'gross mean' is used to denote the quotient of two accumulated values, in this case the total production of 36 orchards as a function of their planted area.

sample of the respondents supplied fertiliser returns, so the indirect energy reported for intensive orchards was inconclusive. It is not known whether intensive apple regimes are as efficient as conventional in terms of total mineral conservation. Physically smaller trees should require proportionally smaller machinery, with savings in capital inputs, resulting in compensatory efficiencies in indirect inputs. No net increase in direct energy inputs relative to production regimes was observed.

4.1.2 Analysis of energy intensity

The mean energy intensity (per area) was 54.7 GJ ha^{-1}, ranging from 34 GJ ha^{-1} to 135 GJ ha^{-1}. This result can be compared with previously reported values:
- low density, non-irrigated young trees　　　　40.9 GJ ha^{-1}
- high density, irrigated young trees　　　　　58.0 GJ ha^{-1}
- high density (trellis) irrigated mature trees 170 GJ ha^{-1}　　(Pimentel, 1980)
- New Zealand kiwifruit study　　　　　　　49.1 GJ ha^{-1}　　(Barbour, 2001)

There was an anecdotal reduction in the energy intensity (per area) values as orchard size increased (Fig. 6). That is, larger orchards were more energy efficient, and some, but not all, small orchards were relatively inefficient. Neither the OFP orchards nor the intensive orchards stood out as being outside of this overall distribution. The OFP orchards had a higher mean, but the difference was not statistically significant (App. III.II, p225). The high results included an orchard (HB-13) that was affected by high
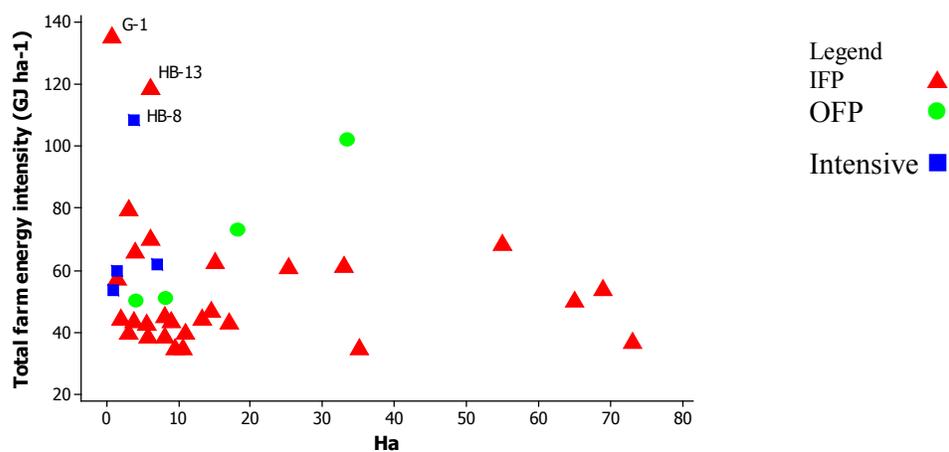
Figure 6: Total farm energy intensity (GJ ha^{-1}) by orchard size

(Range 34.4 – 134.9, mean 58.1, median 50.9, gross mean 55). The larger orchards exhibited an anecdotal reducing trend, and a (predictable) reduction in extreme values.

fuel inputs, suggesting either inefficient practices, or a pest and disease issue. Two small orchards (intensive HB-8, and conventional G-1) revealed a separate issue. While their direct and indirect inputs were all quite high, high capital inputs significantly affected the total. These cases suffered from an inverse economy-of-scale effect. The growers owned a range of machinery required for various orchard processes. However, the individual items of machinery (particularly tractors) would have met the requirements of a much larger operation. Orchard machinery is scaled to fit tree rows, not the size of the operation, so small orchards inevitably suffer from higher capital inputs unless they engage in sharing or co-operative strategies for capital equipment. The conclusion reached by Mila` i Canals (2003) that the contributions to emissions were site specific applied to this energy distribution. This conclusion is important, as site specificity (and season specificity) is a consistent theme through this energy study, showing that strategies for improvement need to be flexible enough to address the differing requirements of individual operations, with scale being identified as a significant variable. The energy intensity (per crop) revealed a similar distribution against orchard size (Fig. 7). An outlying value (HB-17) was reported to be in a development phase. An interpretation is that some small orchards suffered from the inverse economy-of- scale effect noted earlier, while others adopted strategies such as equipment sharing, which allowed them to perform as well as, or better than larger operations. Here again, the organic and intensive systems could not be distinguished from the wider distribution (Fig. 7).
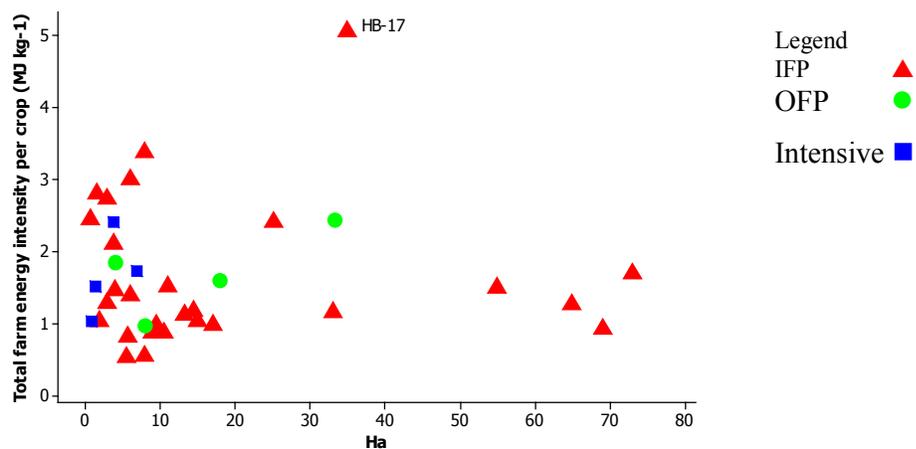
Figure 7: Total farm energy intensity (MJ kg^{-1}) per gross production volume

A question was considered as to whether second order relationships existed between the energy indicators (Fig. 8). While relationships were found, the statistical significance must be treated with caution as one component (either mass, energy or area) is represented in both the independent and dependent variable in every case. The results can be contrasted with the horticultural glasshouse situation, where productivity is (positively) dependant on energy inputs (Hatirli *et al*., 2006). Apple orchards that were more *productive* in terms of energy were also more productive in terms of land area (Fig 8a), and conversely, orchards that incurred high energy inputs per volume of crop achieved the lowest productivity in terms of land area (8b). Similarly, orchards that expended more energy per hectare, also incurred a higher energy cost per mass of crop produced (Fig. 8c). Lastly, there was no significant relationship between production intensity and energy intensity per area (Fig. 8d) (see also App. III.VII, p228). These relationships can be understood in terms of orchard energy inputs being determined primarily by pest and disease management and (in some instances) irrigation practices. Higher energy inputs reflected adverse growing
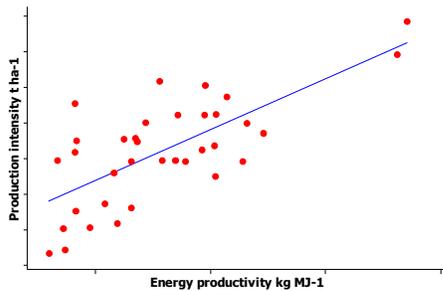
Fig. 8a Production intensity vs. energy productivity

t ha^{-1} = 19.5 + 28.7 kg MJ^{-1} (p =0.000)
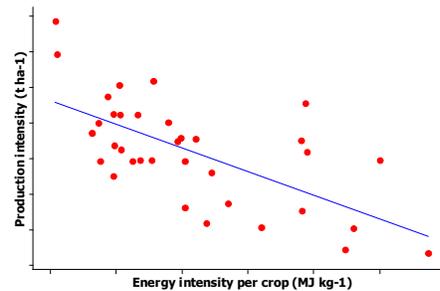
Fig. 8b Production intensity vs energy

intensity t ha-1 = 62.9 - 13.4 MJ kg-1 (p=0.000)
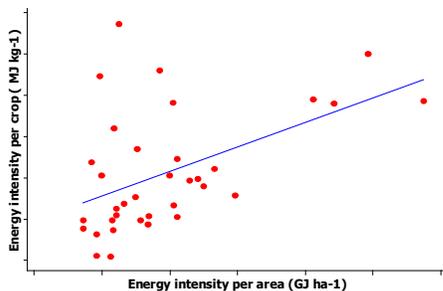
Fig. 8c Energy intensity (per crop) vs. (per area)

MJ kg-1 = 0.685 + 0.0149 GJ ha-1 (p = 0.003)
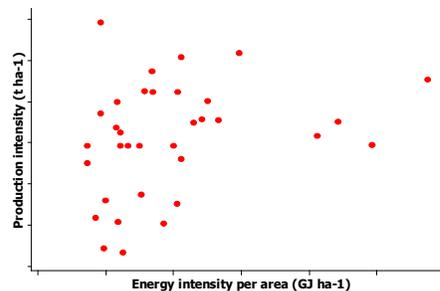
Fig. 8d Production intensity vs. energy

intensity (per area)

Figure 8. Second order relationships between energy indicators

conditions, a situation that was reflected in poorer crop yields. There was little variation in overall energy intensity between regions. The only statistically significant difference was the Gisborne result expressed as function of planted area (see App. III.III, p226).

4.1.2.1 Direct energy inputs

When direct energy use was measured as a function of area (Fig. 9) there were no significant regional differences. Fuel use was the largest component of direct energy, averaging 18.0 GJ ha^{-1}, comprising 32% of the total energy inputs. The striking feature of this data set was the scale of variation (Fig. 10) measured against production area (1.6 GJ ha^{-1} to 68.9 GJ ha^{-1}).
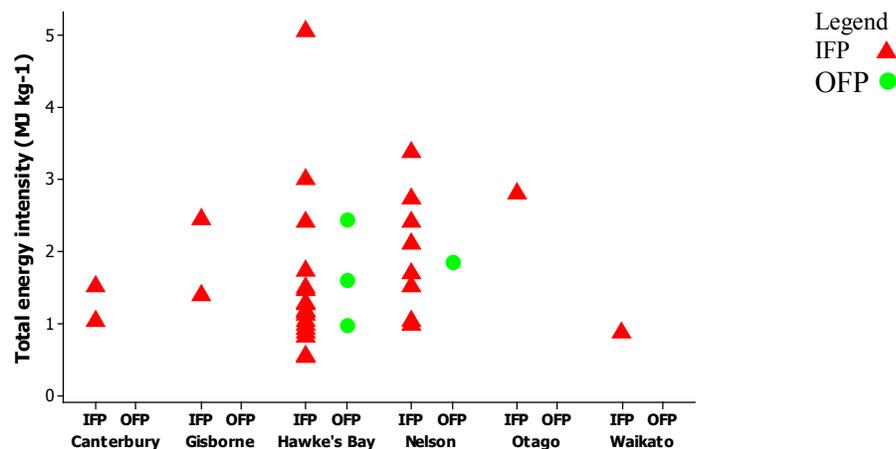
Figure 9: Fuel energy intensity (GJ ha^{-1}) by region and production system

The main regions were comparable, and the OFP orchards fell within the distribution

The highest value (HB-13) is questionable, as in this case the hectarage was not reported, and was estimated from production volumes. The distribution of fuel energy intensity (Fig. 11) returned results for two marginal growing regions, Gisborne and Waikato, that were in the extreme value range for the main regions. The Gisborne observation reflected a warmer, wetter climate while the Waikato result suggested a higher proportion of fruit had been grown for local markets, requiring lower agrichemical inputs than export fruit. Both the OFP and intensive orchards were distributed within the range of fuel use data (Fig. 12), demonstrating that neither of these alternative systems demanded higher direct energy inputs. There were no
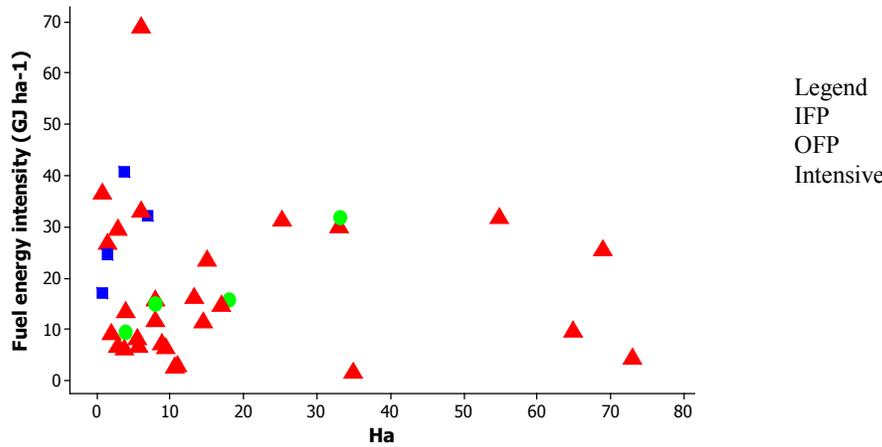
Figure 10: Fuel energy intensity (GJ ha^{-1}) against orchard size

(Range 1.6 – 68.9, mean 18.9, median 15.5, gross mean 18.0.) Fuel use was the dominant driver of farm level energy inputs.
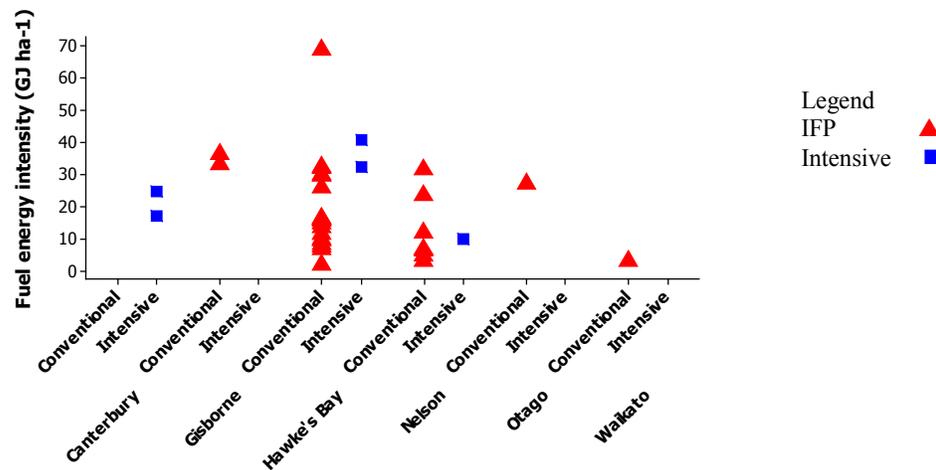
Figure 11: Direct (fuel) energy intensity by region and growing system

Fuel use in the intensive orchards fell within the overall distribution.

obvious patterns with respect to production systems or growing systems between direct energy use (including electricity) and crop yield (Fig. 12) although a wide range of values was returned. However, a simple relationship between production volume and direct energy inputs was apparent (Fig. 13), confirming that production was dependent on direct energy inputs. A difference in direct energy intensity between
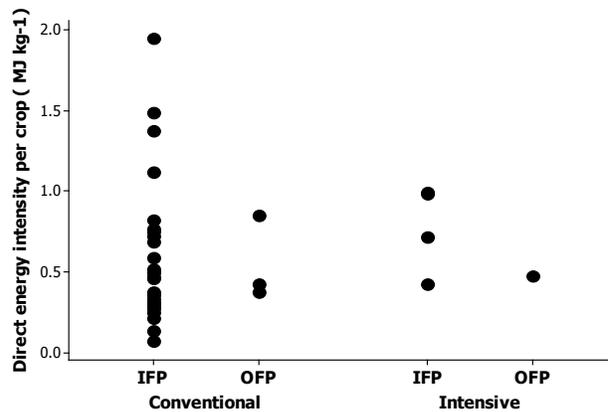
Figure 12: Direct energy intensity (MJ kg^{-1}) for production and growing systems
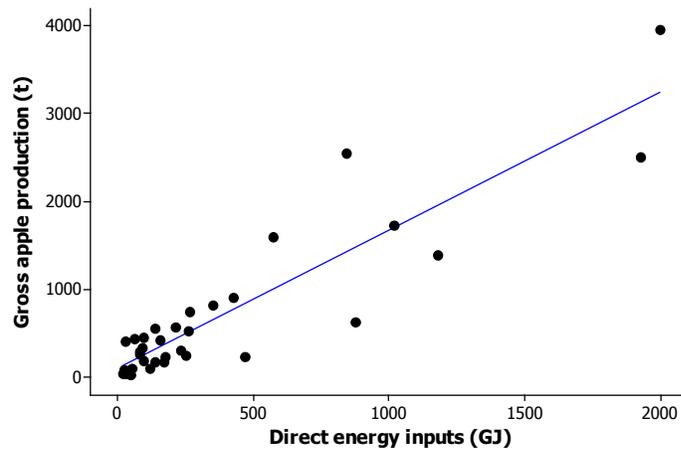
Figure 13: Gross production as a function of direct energy inputs

Regression: production (t) = 96.3 + 1.6 direct inputs (GJ). (Correlation 0.908, p-value = 0.000)

the main regions (Hawke's Bay and Nelson / Marlborough) was noted, with a concentration of Nelson / Marlborough orchards at the lower end of the distribution (Fig. 14). This regional difference is further underscored by the regional medians (Hawke's Bay 19.4 GJ ha^{-1}, Nelson 9.9 GJ ha^{-1}). It is possible that the differences can be explained purely in terms of seasonal spraying requirements. This possibility is supported by the agrichemical energy inputs, with Nelson's inputs averaging 60% of the inputs for Hawke's Bay.

However, in spite of this regional difference, some Hawke's Bay orchards were represented at the lowest end of the distribution, so the differences cannot be
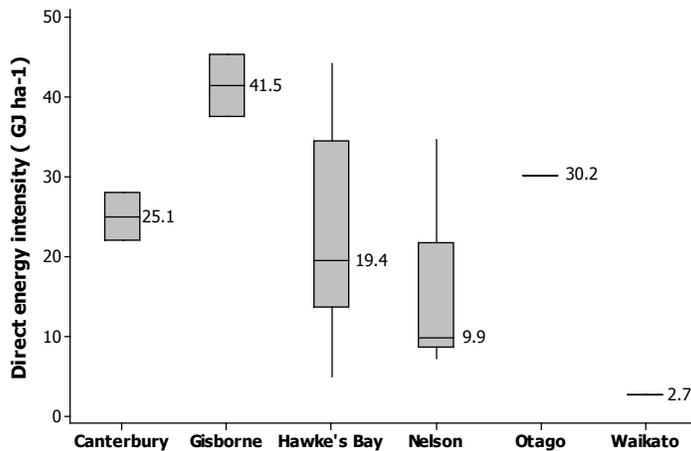
Figure 14: Regional differences in direct energy intensity

explained entirely by regional climatic differences. There was however some
evidence of the anecdotal trend observed earlier (Fig. 6) of larger orchards being more
energy efficient. The wide range of direct energy intensity values (as a function of
production) dropped as orchard size increased (Fig. 15). However, the lowest and
highest values were evident in smaller orchards, and the sample size of very large
orchards was small, so this result can also only be regarded as anecdotal.
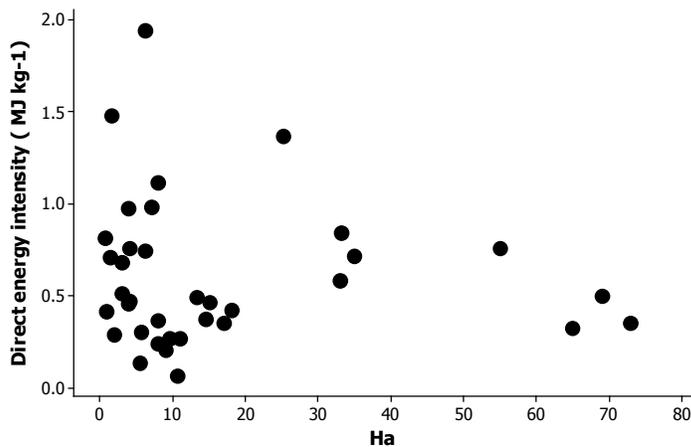
Figure 15: Direct energy intensity (MJ kg^{-1}) versus orchard size

4.1.2.1.1 Electricity inputs

Electricity energy usage observations were obtained for 14 / 36 respondents. The
major component of orchard electrical energy use was pumping for irrigation. Some
orchards also reported using electrical wind machines for frost protection. Electrical

energy comprised 6% of the mean energy inputs. The values of electrical inputs varied from nil to 20.6 GJ ha^{-1}. The nil value is reasonable, as the major contributor to electrical usage is irrigation, and that process can be equally performed with fuel energy (by tractor PTO, or diesel generator set). It is quite possible, although from the evidence of these results unusual, to operate an orchard without electricity.

4.1.2.1.2 Irrigation inputs

Irrigation inputs in apple production vary widely from region to region, depending on soil type, and from season to season. The single Waikato respondent submitted the nil data point for electricity use, so the lack of irrigation inputs is understandable in view of that region's high rainfall (McKenzie, 1987). On the other hand, the single high value of 20.6 GJ ha^{-1} could have resulted from greater irrigation inputs on a light soil type. However this particular value may have resulted from the inclusion of workshop electrical usage on a relatively small (4 ha) orchard, despite the potential inclusion of inputs not attributable to the crop being anticipated in the survey methodology (App. VII, p255).

4.1.2.1.3 Direct energy inputs summary

Direct energy inputs, which consist of the sum of fuel and electrical inputs, comprised 38% (21.3 GJ ha^{-1}) of the total energy usage, and represent a significant opportunity for energy reduction. Direct inputs are a natural group, in that all the inputs are theoretically exchangeable. For example wind frost protection can equally be performed by electrical energy or fossil fuel. Although the most obvious differences within the survey data can be explained by factors beyond the control of growers, some of the variation cannot be easily explained, and may offer opportunities for industry wide improvement by identifying best practice.

4.1.2.2 Indirect energy inputs

The indirect energy analysis was based on a sub-sample of 27 orchards (Sections 3.2.3.1, 3.2.3.2). A significant difference (at 95% confidence level) was found between IFP and OFP indirect energy intensity by area (GJ ha^{-1}) but not by crop (GJ kg^{-1}). No differences were found between intensive and conventional systems (App. III.VIII, p229). The OFP orchards featured in the higher observations (Figs. 16, 17),

resulting in a skewed distribution driven by agrichemicals rather than fertiliser (Fig.
17). Three of the four highest results (HB-15, HB-3 and NE-11) were large OFP
orchards that provided a reliable indication of normal OFP practice. A high fertiliser
input contributed to the other high observation (G-1, a small IFP orchard in Gisborne).
OFP agrichemicals are less efficacious than the sophisticated formulations developed
for IFP programmes, requiring more concentrated applications at shorter intervals,
resulting in higher agrichemical energy inputs. The intensive orchards trended toward
the lower end of the distribution - results that may have been masked by the
management of intensive blocks in combination with conventional blocks (the
arbitrary cut-off being 40% or more intensive by planted area, Sect. 3.1.2.1).
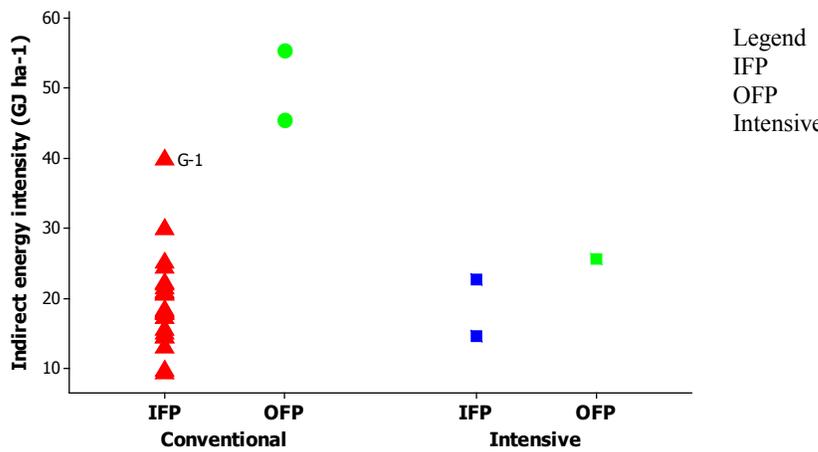
**Figure 16: Indirect energy intensity (GJ ha^{-1}) by growing and production
systems.** (Range 9.3 - 55.5, mean 22.0, median 17.9, gross mean 22.0).
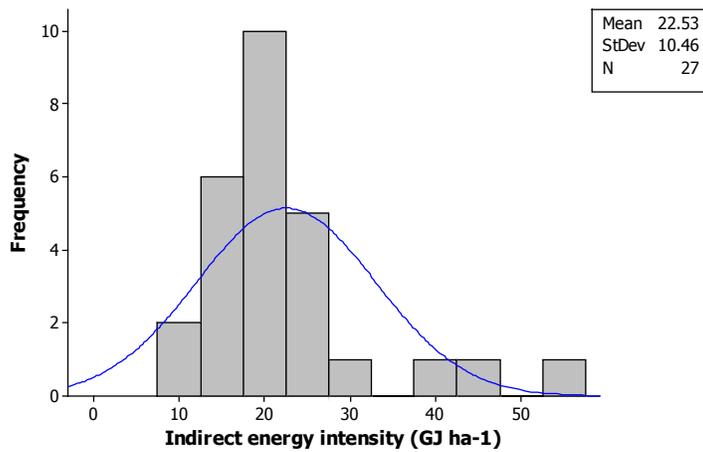
Figure 17: Indirect energy intensity distribution (GJ ha^{-1})

4.1.2.2.1 Fertiliser

Fertiliser comprised 16% (8.6 GJ ha^{-1}) of the total energy inputs[29]. In comparison, fertiliser comprised 35% of total energy inputs in the national average dairy farm (Wells, 2003). A value of 12.6 GJ ha^{-1} has been reported in a kiwifruit study (Barber, 2004b). Organic fertiliser energy values (calculated as a case study for HB-3, an 18 ha organic orchard) placed this orchard's inputs (12.4 GJ ha^{-1}) above, but reasonably close to the mean (8.6 GJ ha^{-1}), however there was a higher level of uncertainty in these calculations than for inorganic fertilisers. The total energy content of the fertilisers applied by the fertiliser sample group reveals high levels of nitrogen, calcium and phosphorus and potassium being applied (Fig. 18). This result is reasonably consistent with the fruit mineral removal rates (Palmer and Dryden, 2006) summarised in Sect. 4.1.1.3 [30], although phosphorus applications were higher than would be anticipated.
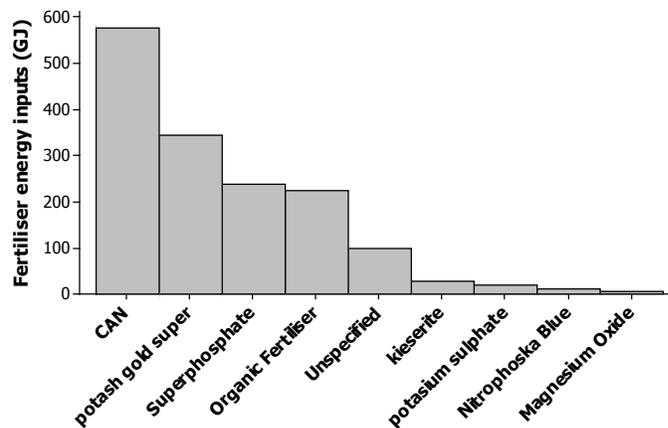
Figure 18: The embodied energy of fertilisers, excluding urea, applied to 9 / 36 orchards

Although all the orchards (except G-1) were from the Hawke's Bay region, they covered a range of soil types from the light, shallow Takapau silt loam to the deep alluvial Hastings and Twyford silt loam series[31] (Griffiths, 1997). In the sample group there was no obvious relationship between soil type and input energy,

---

[29] See Ch 3.2.3.2 for methodology, and App. I (p201) for supporting notes
[30] Mineral balances in apple orchards have been detailed by Haynes and Goh (1980)
[31] The extent to which geographical details have been reported was restricted by commitments to maintain the anonymity of contributing orchards.

suggesting that even the rich Hastings and Twyford soils were being managed as 'steady state' systems, rather than being 'mined' for minerals (Table 9). (See App. X, CD ROM, for fertiliser applications and energy calculations).

Table 9: Energy content of fertiliser by orchard

Orchard	Total embodied energy (GJ)	Orchard area (ha)	Energy intensity per area (GJ ha^{-1})	Energy intensity per crop (MJ kg^{-1})	Soil Type
HB-4	23	3	7.8	0.13	Flaxmere silt loam
G-1	19	0.75	25.2	0.45	Matawhero silt loam
HB-2	697	55	12.7	0.28	Takapau silt loam
HB-11	72	17	4.2	0.10	Twyford silt loam
HB-12	22	8	2.7	0.04	Twyford silt loam
HB-3	223	18	12.4	0.27	Hastings clay loam
HB-8	49	3.8	12.8	0.28	Hastings silt loam
HB-16	30	5.7	5.3	0.11	Moteo silt loam
HB-1	410	69	5.9	0.10	Takapau silt loam
Gross mean			8.6	0.17	

Although the sample (mean 9.9 GJ ha^{-1}, standard deviation 6.9), appeared to be unduly influenced by the G-1 result the values adopted were the gross means (the quotient of total energy and total area [total crop]), which reduced the influence of the small block. This provided a benchmark value of 8.6 GJ ha^{-1} [0.17 MJ kg^{-1}].

A tree or field crop invariably incurs the removal of nutrients from a production system, in the form of chemical elements and compounds. In the New Zealand apple industry, because a large proportion of the crop is exported, there is limited opportunity to recycle nutrients into the growing system (Goh and Haynes, 1983, Palmer and Dryden, 2006). Some of these nutrients are derived from the weathering of rocks and minerals in the parent material, while others are added in the form of

fertiliser. A benchmark value for fertiliser inputs could arguably be modelled on a steady state system, with removal rates balanced by inputs.

In observed practice, growers apply fertiliser as a response to recommendations (by consultants) in response to annual soil and leaf mineral analyses. Soils represent a dynamic interaction of a mineral substrate with the wider ecosystem. This interaction involves climatic factors, the specific requirements of crops and also management practice, resulting in substantial variability between orchards, within individual orchards and between seasons. Nitrogen, a key nutrient, is available as fixed atmospheric nitrates. Nevertheless, in practice fixed nitrogen was invariably supplemented with mineral fertilisers.

Fertilisers containing a high proportion of nitrogen have a significantly higher energy content than that of other fertilisers, their manufacture being based on fossil fuels (usually natural gas). Urea usage was certainly relevant, but not as significant as that reported by Poe (2003). The overall contribution of urea was 3%, averaging 1.6 GJ ha^{-1} overall. Just 18 of the 36 respondents reported urea use. The contribution in five cases was over 8% of their individual energy input, and in one case over 20%. Nevertheless, the highest individual energy input from mineral fertilisers excluding urea was calcium ammonium nitrate (CAN) (Fig. 18). These results confirm the sensitivity of individual cases to nitrogen inputs. The direct link to fossil fuels is a critical aspect of the energy content of fertilisers from both a cost and a sustainability perspective.

4.1.2.2.2 Agrichemicals

Notes on the methodology for deriving values for agrichemicals are presented in Sect. 3.2.3.1 (see App. II, p221, App. IX, p269)

The energy content of agrichemicals comprised 21% of the total energy inputs, however the overall mean (11.4 GJ ha^{-1}) was weighted towards the contribution of the organic orchards. The mean for the IFP orchards measured was 6.5 GJ ha^{-1}, while the mean of the OFP orchards was 28.5 GJ ha^{-1}. The difference was statistically significant (App. III.VIII, p229). This result was sensitive to the energy co-efficient

for the organic formulation lime sulphur (App. I, p215).   The energy intensity
measured against both crop and land area showed a similar pattern. The two higher
observations for OFP agrichemical usage (Fig. 19) can be attributed to practices for
the prevention of fungal diseases such as apple scab (Holb *et al.*, 2003).
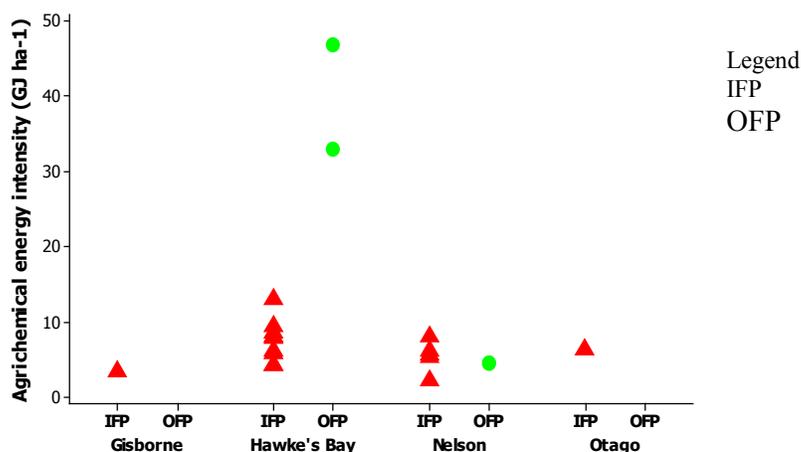
Figure 19: Agrichemical energy intensity as function of planted area

(Range 2.3 – 46.9, mean 9.9, median 6.1, gross mean 11.7). Energy inputs were calculated for 19 / 36
orchards, two of the three OFP orchards featuring as outlying data points.

Apart from the organic orchards, the agrichemical energy inputs varied from 2.2 GJ
ha^{-1} to 13 GJ ha^{-1}. The regional difference noted for direct contributions (Fig. 12) was
also apparent, with Nelson orchards grouped in the lower half, and Hawke's Bay
higher. This difference pointed to the normal variability that could be expected to
occur between seasons, as well as between districts in any particular season. (New
Zealand's geographical situation in the 'roaring forties' latitude, its longitudinal
position to the east of Australia, and geomorphology - derived from active tectonic
geology - combine to produce a highly variable climate). However, the Hawke's Bay
organic orchards stood out as having higher agrichemical energy intensity (shown in
Fig. 20 as a function of production). The Hawke's Bay IFP agrichemical energy
intensity was comparable to the Nelson region, while the Hawke's Bay OFP result
influenced the higher regional energy intensity indicator values. This result casts
doubt on the climatic explanation, suggesting that management practice might be a
causal factor. However, the small OFP sample group was highly case sensitive.
The difference between OFP and IFP regimes is still apparent as a function of
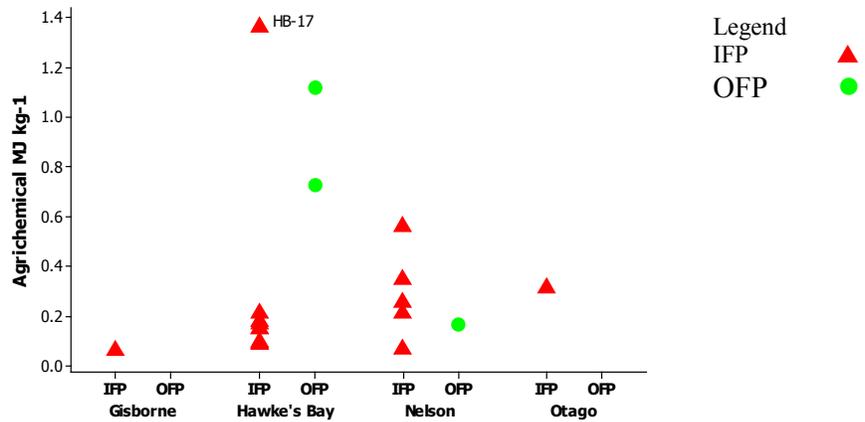
Figure 20: Agrichemical energy intensity as a function of production

production volume, but not so extreme as the per area situation (Fig. 19). The case of a block in a redevelopment phase (HB-17) is the extreme data point. This grower applied normal quantities of agrichemicals, but only achieved a small crop.

A Pareto analysis of OFP case HB-3 identified the 'vital few' contributions (Fig. 21). In this case a single formulation (lime sulphur) constituted the key input, while a Pareto analysis of a representative IFP case (HB-2) identified six inputs that fell within the 80% cumulative graph (Fig. 22, Table 10).

When the energy content was sorted by functional type, fungicides were the highest. The actual order was case-specific, depending not only on the energy content of the active ingredient, but the formulation and concentration of the application.

Table 10: The top six agrichemical energy inputs for IFP orchard HB-2

Trade name	Active ingredient	Function
Roundup Renew	glyphosate	herbicide
Thin-It S	ammonium thiosulphate	fruitlet thinning
Syllit Plus	dodine	fungicide
Caltex D-C-Tron Nr	mineral oil and petroleum distillates	winter oil
Captan Flo	ethyl mercaptan	fungicide
Match	Lufenuron	insecticide
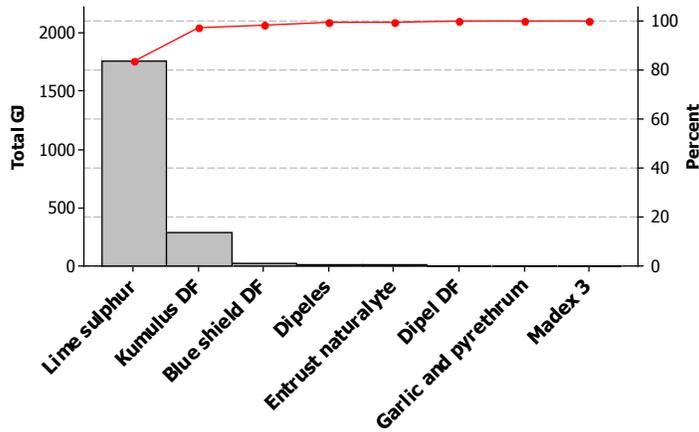
Figure 21: Pareto chart of energy inputs in OFP agrichemicals (orchard HB-3)

The fungicidal treatment lime sulphur alone exceeded the critical 80% cumulative level of the Pareto analysis.
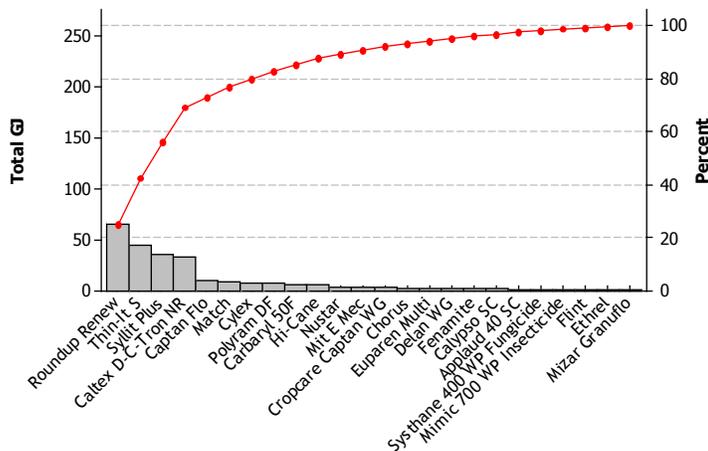
Figure 22: Pareto chart of HB-2 agrichemical inputs

In the IFP case, seven agrichemicals fall beneath the 80% cumulative line, including a herbicide, a thinning treatment, two fungicides and winter oil.

4.1.2.2.3 Indirect inputs summary

Indirect inputs excluding capital equipment formed 40% of the total inputs. Indirect inputs were not found to be a natural group with respect to forming strategies for energy use reduction as the issues surrounding those inputs were highly case specific. For example, within fertilisers, urea stood out as an input to which individual cases were sensitive. It would be more useful to focus on each sub-group independently

4.1.2.3 Capital inputs

The capital inputs measured comprised 22% of the energy content of apples. Note that an energy analysis differs from a financial analysis in that crop items (i.e. trees) are not included as capital. Capital items accounted as contributions to the energy analysis include all buildings, machinery and plant and structural materials used in the production process. For a description of the methodology for calculating capital energy inputs, see App. I.IV, p 218, and for the calculations, see App. X, spreadsheet "Orchard energy summary.xls, sheet "Capital energy calculations".

Economies of scale were achieved by larger operations, with smaller operations below 6-7 ha being disadvantaged (Fig. 23). However beyond about 10 ha, there did not appear to be any advantage. The organic orchard HB-3 achieved the lowest result by sharing equipment with other orchards.
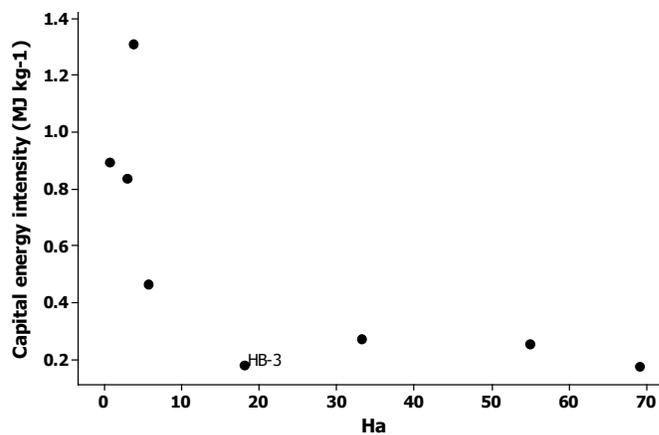
Figure 23: Capital energy intensity (MJ kg^{-1}) by orchard size

The efficiency of scale achieved by larger operations is demonstrated. Conversely, the high relative energy cost incurred by equipment in small orchards is clear.

4.1.3 Themes

In this section the energy picture is analysed with reference to various themes of interest to the grower.

4.1.3.1 Energy and organic production

OFP orchards have been examined closely by various researchers (see Sect. 2.2) in attempts to determine whether or not they are more sustainable than IFP operations. The results of this study contribute to this discussion.

There are aspects of the OFP process that clearly consumed more energy than related aspects of IFP operations. The single greatest area in which organic orchards appeared to be disadvantaged is in the energy embodied in agrichemicals. The total energy embodied in the high volumes of copper and sulphur-based pesticides certainly exceeded the energy content of chemicals used in IFP programmes. However, even if a comparison were restricted to these processes, energy consumption would provide a limited perspective. Mila` i Canals (2003) discussed aspects such as the human and ecological toxicity of emissions from both types of systems. That study showed that each system had both advantages and disadvantages, and suggested site specificity as a greater contributor to the overall impacts than either OFP or IFP protocols.

Measurements of the energy content of organic fertilisers placed them in the same order as inorganic fertilisers so, as a consequence of the higher energy content of organic pesticides, the resulting total indirect energy inputs for OFP operations were at the high end of the distribution (Fig. 16). However comparing inorganic fertilisers to organic compost fertilisers on the basis of energy content would be inadequate. For example, crop yields have been reported to be consistently higher when a combination of organic and inorganic fertilisers were used than when either was applied in isolation (Parr and Colacicco, 1987). OFP orchards sat centrally in most of the reported energy distributions. Surprisingly, in view of the acerbated requirement for spray applications, OFP orchards did not use more fuel than IFP orchards, but again fell in the middle of the distribution (Fig. 9).

A conclusion that might be safely drawn is that the production systems of major OFP inputs, specifically the inorganic copper and sulphur pesticides should be examined closely. Modern organic production has been criticised as being compliance orientated, rather than orientated toward the principles from which it evolved (Rigby and Bown, 2003, Rigby and Bown, 2007). To address this criticism, and pre-empt

market resistance, the industry might articulate a value system that would define the standards by which competing suppliers should be compared.

4.1.3.2 The IFP picture

The results of this study have demonstrated that IFP protocols have a critical function in reducing energy inputs. Reducing the application of pesticides (which is a primary objective of the IFP framework) impacts on direct inputs through the reduction of fuel usage, and on indirect inputs through the reduction of agrichemical energy inputs.

In the execution of the present study, the lack of energy data for the production systems of agrichemicals created significant uncertainties. An anomaly was identified in that the customers of New Zealand apple producers audit apple production systems for both biosecurity and environmental compliance, yet the production systems of agrichemical suppliers are largely unknown. The principle of extending quality assurance to suppliers is firmly established in quality literature (Beckford, 1998). If the principles to which global food suppliers are required to adhere were to be adopted for their suppliers, the onus to supply and substantiate sustainability data would be placed on the manufacturers.

4.1.3.3 Economies of scale

A trend across energy parameters was for a positive relationship between energy efficiency and orchard size. However, there were several exceptions in which small orchards perform very well. A small cluster of orchards of less than about 8ha exhibited high energy intensity (per area) values (Fig. 6). The large orchards performed consistently well, albeit represented by a small sample group. This trend was particularly clear in the area of capital energy (Fig. 23) where small orchards were seen to have more equipment than necessary. If the industry wished to address this issue, it would be relatively straightforward for small orchards to become more efficient by sharing equipment, or forming co-operative groups.

4.1.3.4 Intensive versus conventional

The results of this investigation did not demonstrate any statistically significant trends with respect to intensive plantings. The two possible conclusions offered are that

either there were in fact no significant differences, or that the results were diluted by the inability of the top-down methodology to distinguish between the intensive blocks and the conventional blocks they were managed alongside. Nevertheless, the energy characteristics of intensive apple production can be considered from observation of practice.

In the most general terms, a move toward intensive farming can be argued to be a movement away from sustainability. That is, there are limits to how intensive farming can become without harming the environment (Giampietro, 2004). Nevertheless, it would appear that orchard production could move in the direction of becoming more intensive without becoming less sustainable. The three input areas (direct, indirect and capital) can be considered separately:

The direct inputs are fuel and electricity. The largest process component of fuel usage is spraying for pest and disease management (Mila` i Canals, 2003). An intensive planting model should result in an energy usage decrease as the total tree row volume fills a smaller vertical space more efficiently (Palmer and Dryden, 2006). There would be a trade-off between the requirement for more passes through the block, and a reduced horsepower requirement to achieve coverage for smaller trees. Other fuel consuming processes (mowing, mulching) should also require less rather than more fuel as the intensive planting would involve a smaller grassed area, and less vigorous trees. A likely result of a move toward higher density plantings is a small reduction in fuel usage on a per hectare basis, but a significant improvement in the ratio of crop output to fuel inputs.

The primary component of electricity usage is irrigation. Intensive plantings would probably require slightly higher irrigation inputs. However, existing irrigation systems typically involve a degree of water wastage when water falls outside the root-zone of trees, to be transpired by competitive grasses, or lost through infiltration to groundwater. Intensive plantings should be able to utilise water more efficiently (Li *et al.*, 2002). The overall result for direct energy usage should be an improvement, and hence a move toward sustainability rather than away from it.

In a steady state system, the inputs of nutrients should balance what is taken out as a crop. It follows that fertiliser inputs should need to be increased in proportion to increases in the crop. Consequently, for intensive plantings there should be no change in energy intensity with respect to the crop, but an increase relative to the land area. Agrichemical usage would follow a similar pattern to fuel usage. An intensive planting with smaller trees, but more rows should if anything, require smaller pesticide volumes rather than greater. There may be disease or other management issues with respect to varieties and rootstocks that negate any advantage here, but again the overall result should be little change on a per hectare basis, and a significant improvement relative to crop volumes.

Capital inputs contributed 22% of the total system energy inputs (Fig. 3). An intensive regime should allow some reduction in the size and therefore mass of machinery. Buildings and tracks should not change, but irrigation, post and wires might well increase. Overall, the capital energy inputs are likely to be less if anything on a per hectare basis, and should be significantly less relative to improved crop yields over the lifetime of the planting. (Note that in a financial model, the term 'capital' takes a different meaning, and is based on financial outlay). Overall, it is argued from an energy perspective that the apple industry could move some distance toward intensifying production without compromising sustainability.

4.1.3.5 Site and season specificity

The results of this study are consistent with the conclusions of a previous study of New Zealand apple orchards (Milà ì Canals, 2003). While patterns of energy use are evident across regions and production systems, the variability is determined by a range of interacting factors specific to individual cases, sites and seasons. As a result of this, strategies for energy reduction will have to be designed to be flexible and adaptable to each grower's specific set of circumstances.

4.2. Post-harvest case studies

4.2.1 Introduction to case studies

Case study one (CS-1) and two (CS-2) were based on data provided by two organisations. CS-1 was situated in the Hawke's Bay region, and could be considered medium scale in terms of the New Zealand apple industry, while CS-2 was a slightly smaller operation situated in the Nelson region. Both organisations were relatively self-contained, managing bodies of product that remained relatively discrete, and under their management throughout the post-harvest value chain. Of equal importance to the study was that the data they submitted was not compromised by the passage of large volumes of other products through their post-harvest facilities (a significant complicating factor for larger post-harvest organisations). Both organisations owned or leased packing and cool-store facilities on single sites.

CS-1 was a post-harvest fruit processing company sited 23 km from the Port of Napier. This organisation received between 22,000 and 50,000 tonnes of apples per year in the four seasons 2004-2007. In 2007 it received 17 varieties of apples from over forty different growers providing a range of data for energy analysis, including electricity usage and crop data covering all or part of five seasons (from 2003-2007).

CS-2 was a Nelson region post-harvest fruit processing company. The operation site had a single packing facility and cool-storage facilities. Data was submitted for ten supplying orchards over two seasons (2006 and 2007). Gross and export crop volumes were provided for 2007 and export volumes only for 2006. The organisation processed 16566 tonnes of apples in 2007 (reported) and 14440 tonnes in 2006 (estimated from reported export volumes). The components and methods (Table 11) are detailed in Sect. 3.3.

4.2.2 Energy usage of lift-trucks (forklifts)

Lift-trucks are a ubiquitous feature of post-harvest facilities. The environmental burden incurred has been assessed through carbon footprint methodologies. Johnson (2008) provided a review and comparison of several studies, describing an apparent

disagreement in assessing the relative costs of LPG and electric lift-trucks. He concluded that the disagreement was caused primarily by differences in definitions and boundary choices, and reported that the carbon footprints of LPG and electric lift-trucks were similar but that LPG was marginally preferable. Other researchers differed (Elgowainy *et al.*, 2009), rating battery lift-trucks (and fuel cell lift-trucks) higher than LPG lift-trucks. The critical assumption here was the source of electrical power. The New Zealand case, benefiting from a high proportion of renewable power generation, could be argued to favour battery lift-trucks.

For both case studies, the direct electrical energy component for lift-trucks was contained within the total energy (kWh) attributed to packing and cooling, so this component was estimated on the basis of the relative mass of different forklift types (Table 12). CS-1 provided an average fuel estimate of 80 litres LPG per day, which was allocated on the basis of a 250 working day season.

4.2.3 Indirect energy attributable to lift-trucks and batteries

Packhouse and cool-store facilities deploy a range of lift-truck sizes. Battery powered lift-trucks are used almost exclusively inside buildings because of their low emission profile, with LPG and diesel machines being used for exterior work. Lift-trucks deployed in apple packing facilities are reported to range in mass from 1.8 t to 3.0 t. The size profile of machines working in the confined spaces of cool-stores is more constrained than that of machines working in exterior spaces, so battery powered lift-trucks typically represent the lower and middle range of machine weights, while LPG and diesel lift-trucks occupy the higher range (Elgowainy *et al.*, 2009).   Sources of variation included the layout of buildings and plant, processes specific to individual sites and the specifications and performance of lift-truck designs (GiantBatteryCo, 2009). The two cases showed quite close agreement (Table 13).

In CS-1 most of the machines were hired for the duration of the season (approximately January to August), while some were retained all year or purchased by the company. In CS-2 three fuel lift-trucks were owned, and a further two diesel, and three electric were hired from February to June. A proportion (75%) of the indirect energy was treated as attributable to the products in both cases.

Table 11: Summary of components of post- harvest energy demand

Component		Mode	Data source/method
Transport	Lift-trucks	Direct	Fuel usage reported.
		Indirect	Estimated (vehicle number and type reported).
	HGV	Direct	Distances from orchard to site, and site to port were reported. Energy usage was calculated from reference values.
		Indirect	
	Shipping	Direct	Distances reported. Energy use was modelled from vessel specifications (n=50) and emission data sourced from literature and industry databases.
		Indirect	Adjusted from published values.
Refrigerated containers		Direct	Refrigerated container energy usage was modelled (for apples).
		Indirect	
Packhouse		Direct	Electricity readings.
			Fruit waxing - fuel usage.
		Indirect	Buildings - measured from site plans. Plant – estimated.
Cool-storage		Direct	Electricity readings.
		Indirect	Buildings – measured from site plans.
			Plant – estimated.
Packaging		Embodied	Model developed from various sources.

4.2.4 Uncertainties in lift-truck indirect energy

In each case, some lift-trucks were hired for 60-80% of a given year, however no information was obtained about their usage in the remaining time. They may have been stored, undergone maintenance or have been hired to other organisations, resulting in further uncertainty in the data.

Table 12: CS-2 direct lift-truck energy intensity (attributed to crop)

	CS-1 lift-truck energy usage		CS-2 2006 lift-truck energy usage		CS-2 2007 lift-truck energy usage	
	Energy content (GJ)	Energy attributed to crop (MJ kg^{-1})	Energy content (GJ)	Energy attributed to crop (MJ kg^{-1})	Energy content (GJ)	Energy attributed to crop (MJ kg^{-1})
LPG	494	0.012	173	0.012	201	0.013
Diesel			191	0.013	108	0.007
Electricity	1924	0.048	116	0.008	133	0.008
Total	2418	0.06	480	0.033	442	0.028

In CS-2, diesel was apportioned 2:1 between waxing (heating) and forklifts (Sect.3.3.4.1).

4.2.5 Heavy goods vehicle (HGV) transport from orchards to packhouse

CS-1 listed a total of 87 supplying orchards. These orchards were owned by about 50 separate commercial entities. It is normal practice for large operations to register discrete growing units separately (registered as 'R-Pins'). These can vary from quite small physical areas (1-2ha) to more than 50 ha. Physical addresses were provided for 58 of these units. The mean distance from block to CS-1 processing site was 10.6 km, and block to port via processing 33.6 km. The majority of CS-1 supplying orchards were clustered in the Heretaunga Plains (McKenzie, 1987), with just two suppliers from the further distant Ruataniwha Plains (Fig. 24). Using a reference value for land transport of 1.4 MJ t^{-1} km^{-1} (Webb, 2004) the land-based transport energy component was 0.054 MJ kg^{-1}. This value is significant because:

- it can be reasonably argued to represent a benchmark value for land transport for New Zealand's largest growing district; and
- the proximity of the growing district to the port contributes favourably to New Zealand's case in the 'food-miles' debate.

Table 13: Summary of the indirect energy embodied in lift-trucks

Lift-truck mass and power source	Units	Battery capacity (kWh)	Battery mass (kg)	Machine embodied energy (GJ yr^{-1})	Battery embodied energy (GJ yr^{-1})	Total energy (GJ yr^{-1})	Energy attributed to crop (MJ kg^{-1})
CS-1							
1.8 t electric	17	33	1180	70.4	24.0	94.4	0.0018
2.5 t electric	8	44	1450	56.1	15.1	71.2	0.0013
3.0 t LPG	6	0	0	120.2	0	120.2	0.0022
Total							0.0053
CS-2							
2.5 t electric	3	44	1450	21	5.7	26.7	0.0013
3.0 t diesel	2	0	0	40	0	40	0.0020
3.0 t LPG	3	0	0	60.1		60.1	0.0029
Total							0.0062

The values in column 7 'Total' were calculated as generic values that might be adopted in further studies. The values in column 8 'Attributed' were attributed to mean gross production.

Once fruit left the packing facility it entered storage inventory pending despatch through the port facilities. At this stage the top-down methodology failed to distinguish the refrigeration energy component of exported fruit from that of co-products such as local market fruit stored in adjoining facilities. In contrast, the transport inputs could fairly be attributed to the exported volumes as a function of distance from port.

CS-2 provided a similar overall picture. The energy values were calculated for the actual volumes of apples submitted to the processor from 10 orchards (compared to the mean distance used to calculate energy inputs in the larger number of suppliers
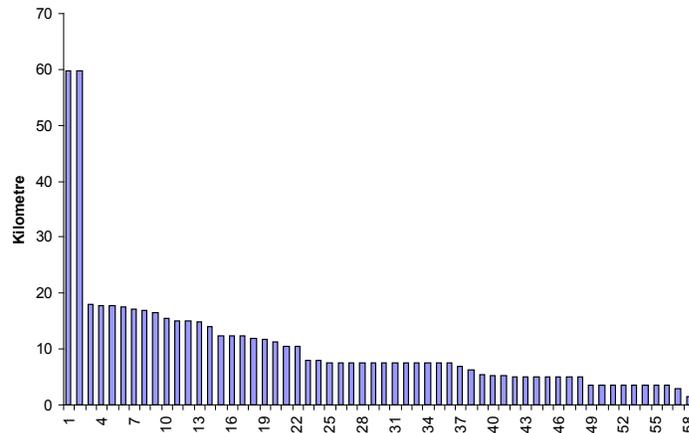
Figure 24: CS-1 supplying orchards - distance from processing site

Observations 4-58 were located in the Heretaunga Plains, while 1-2 were located in the further distant Ruataniwha Plains.

reported for CS-1). Fruit volumes were reported for supplying orchards comprising approximately half of the CS-2 throughput (Table 14).

The total energy inputs (for orchard-packhouse transport) for 2006 and 2007 were respectively 0.0188 MJ kg^{-1} and 0.0190 MJ kg^{-1} (based on the reference value of 1.4 MJ t^{-1} km^{-1} (Webb, 2004)). The energy consumed in transporting fruit from the packhouse-cool-store facility to Nelson Port was attributed to the gross crop[32] as 0.02 MJ kg^{-1}. The total energy consumption for transport from orchard to packhouse to port was 0.040 MJ kg^{-1}. This value was influenced by the proximity of the facilities to the orchards, and siting on a direct route to the port. A further efficiency was gained by the close proximity of the packhouse to the storage facilities, so that trucking was not required between packing and storage.

The two case studies provided similar values for road transport (CS-1 @ 0.054 MJ kg^{-1} and CS-2 @ 0.040 MJ kg^{-1}). Both studies were of growing districts located on rich alluvial soils; sited on coastal plains and river terraces (Griffiths, 1997, Luke, 1968a). Both cases benefited from the proximity of ports.

---

[32] Issues regarding the attribution of energy to gross crop, net crop or export volumes are discussed in Sect. 3.3

Table 14: CS-2 orchard to packhouse energy by volume and distance

Orchard	Distance	2006			2007		
	(km)	Gross	Tonne-	Energy	Gross	Tonne-	Energy
		tonnes	km	(MJ)	tonnes	km	(MJ)
a	9	2,039	18,348	25,687	1,886	16,976	23,767
b	40	945	37,804	52,925	838	33,511	46,916
c	6.5	945	6,143	8,600	838	5,446	7,624
d	10	29	288	404	98	977	1,368
e	10	2,873	28,729	40,221	3,610	36,095	50,534
f	16	60	954	1,335	60	965	1,351
g	17	37	626	877	1	17	24
h	44	0	0	0	176	7,732	10,825
i	7	11	75	105	0	0	0
j	18	12	214	300	0	0	0

The repetition of values between suppliers in rows b and c, and between years in row f can be explained as volumes of fruit contracted for supply to the organisation. It is assumed that production beyond these values was despatched to other organisations.

4.2.6 Packhouse and cool-store direct energy consumption

A major component of direct energy use in the post-harvest facility was electricity usage. In CS-1, usage (MWh) for four cool-store metering sites and a packing shed metering site were reported (Table 15). This demonstrates the energy relationship between packing and cooling. In this operation, packing energy was about 5% of the total electrical inputs to the site. However, the site is unusual in having secondary packing facilities (organic fruit for example is packed in a separate building).

Table 15: CS-1 electricity consumption (MWh) for cool-stores and packhouse

Year	Store 1	Store 2	Store 3	Store 4	Packing shed	Total
2003	674.2	651.9	890.0	2307.2	365.9	4889.2
2004	1014.4	691.3	1375.0	2170.0	338.9	5589.5
2005	884.4	682.1	3341.4	2139.9	264.0	7311.8
2006	485.5	444.7	3775.6	1903.5	340.5	6949.8
2007	649.6	460.2	3172.5	1992.2	270.3	6544.8
Mean	741.6	586.0	2510.9	2102.6	315.9	6257.0

Other packing facilities were assumed to have been metered in conjunction with adjacent cool-store facilities, so the total packing component was estimated to be 10-15%. A relationship was observed in CS-1 between electrical energy inputs and production volumes over the years 2004-07 (Table 16 and Fig. 24).

Table 16: CS-1 direct electrical energy usage as a function of gross production

CS1	Gross production (t)	Electrical energy intensity (MJ kg^{-1})
2004	22553	0.89
2005	49993	0.53
2006	50210	0.50
2007	37636	0.63
Mean		0.64

The apparent negative relationship (between gross production and electrical energy inputs) (Fig. 25) could be argued to indicate inefficiency, or at least an opportunity for improvement, as it should be possible to manage the process so that energy usage is a function of crop throughput. However, cool-store energy usage can equally be argued to be an overhead cost, more or less independent from production throughput. Certainly, an increased throughput must require greater inputs resulting from initial drawdown, but temperature maintenance over time is arguably a function of plant design (including insulation rating) and management practices (Hackett *et al.*, 2005).

On a large site such as CS-1, it may be possible to isolate some stores, and run them at the minimum level required for maintaining seals to prevent refrigerant loss (hence reducing the energy usage in seasons where production is lower). However, in this study the organisation may have leased out more capacity in those years where their own production was reduced, meaning that the reported variation is actually an allocation uncertainty rather than an efficiency issue.
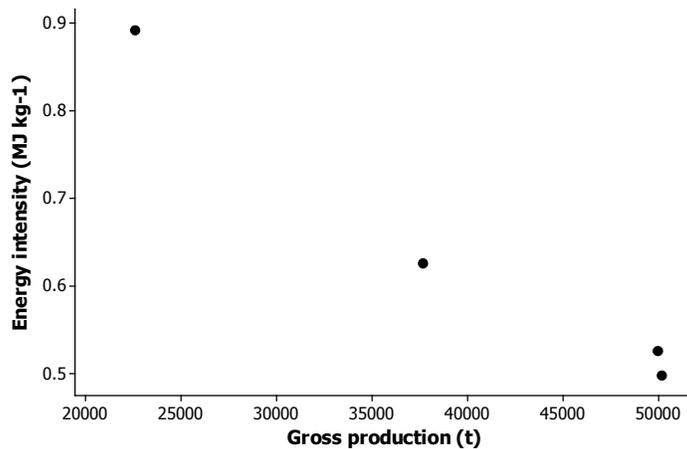
Figure 25: Production volume and electricity usage in CS-1

Management practices have not compensated for reduced production in some seasons by reducing active refrigerated storage capacity.

The total site electrical energy inputs for the two case studies was compared (Table 18). CS-2 used 35% and 46% of the electricity consumed by CS-2 (for 2006-2007). CS-1 appeared to gain no 'efficiency of scale', but rather the smaller scale of CS-2 conferred an advantage. However, a number of uncertainties affect these findings. Firstly, the electricity consumption of the leased store (CS-2 store 2) was not available to me and was estimated. Secondly the volume and turnover of other products in CS-1, including the organisation's own stonefruit operations, and capacity leased to other organisations all constituted uncertainties.

In this summary (Table 17), the values for CS-2 'store 4' belonged to an administration building. The values for CS-2 'store two' were estimated for an adjacent cool-store, for which capacity was leased from another company (Sect.3.3.3). No obvious explanation was found for the difference in electricity usage between the two case studies. The difference may have been due to older, less efficient refrigeration technology in CS-1, and the fact that some of the plant was designed for lower temperature storage than required for apples. CS-2 operated on a large site, with multiple buildings, which may have resulted in inefficient use of space.

There were two opportunities for errors: an estimation error for CS-2, and an attribution error for CS-1. The basis for estimating the power usage of the leased

Table 17: Electrical energy inputs for CS-1 (2004-07) and CS-2 (2006-07)

	Gross (kt)	Export (kt)	Packing usage (MWh)	Store 1 usage (MWh)	Store 2 usage (MWh)	Store 3 usage (MWh)	Store 4 usage (MWh)	Total usage (MWh)	Energy intensity (MJ kg^{-1})
CS-1 07	37.6	27.5	270	650	460	3173	1992	6545	0.63
CS-1 06	50.2	34.4	340	486	445	3776	1903	6950	0.50
CS-1 05	50.0	34.3	264	884	682	3341	2140	7312	0.53
CS1 04	22.6	14.1	339	1014	691	1375	2170	5590	0.89
CS-2 07	16.6	8.0	415	119	400		9.6	944	0.21
CS-2 06	14.4	7.0	392	134	400		11	937	0.23

CS-2 provided an estimation (15%) of the packing facility power consumption at the packhouse meter as attributable to refrigeration or other uses.

building in CS-2 was the capacity of the building. This assumption may have been incorrect. An error of 100% would still place the energy consumption of CS-2 below CS-1.   The electricity usage and company-owned crop throughputs of CS-1 were accurately reported. CS-2 on the other hand reported their crop throughputs accurately, but they were not able to report part of their power usage. On this basis, CS-2 represents a top limit with the possibility of an attribution error, while CS-1 represents a bottom limit, with the possibility of a reporting or estimation error.

4.2.6.1 Waxing fruit

The practice of waxing fruit to enhance appearance (Kupferman, 1984), is widespread in the US and has been adopted by some New Zealand exporters including CS-2, but not CS-1. No prior estimates of the energy consumption of this process were found. The values measured for CS-2 were compared to those observed in a study of a single day's production in a separate Hawke's Bay packhouse (Table 18).   This plant used LPG rather than diesel, and provided a more accurate energy consumption value than CS-2, as the CS-2 diesel source was shared with diesel lift-trucks. The value

calculated in this comparison shows agreement with the mean of the values reported for CS-2. In the absence of other reported energy data for the fruit waxing process, the benchmark value of 0.04 MJ kg^{-1} (export) is offered.

Table 18: CS-2 Fruit waxing energy inputs

CS-2		Comparative one-day study		
	Energy input MJ kg^{-1}	Fuel MJ	Export kg	Energy input MJ kg^{-1}
2006	0.055			
2007	0.027			
mean	0.041	11858	312988	0.038

Waxing energy was attributed to export volumes only (Sect. 3.3.4.1).

4.2.7 The indirect energy component of post-harvest buildings

The embodied energy attributable to the refrigeration plant and packhouse plant (Table 19) and cool-store buildings (Table 20) was calculated as yearly values and as an attribution to the gross production.

Table 19: Embodied energy in refrigeration and packing plant

Plant	CS-1 embodied plant energy		CS-2 embodied plant energy	
	Annual usage (GJ yr^{-1})	Energy intensity (MJ kg^{-1})	Annual usage (GJ yr^{-1})	Energy intensity (MJ kg^{-1})
Refrigeration	248	0.0062	99	0.0056
Packing	0.314	0.0078	0.157	0.0088

See Sect. 3.3.5.1 for methodology. The right-hand columns for each case were attributed to gross production.

4.2.8 Case study uncertainties

An uncertainty (U1) was recognised in that both case study companies had access to other storage sites, from which they lease capacity as required. CS-1 generally had significantly more storage capacity in relation to throughput volume than CS-2. CS-2 specified the proportion of their crop stored in their own facilities as 75%. Another

Table 20: Energy in cool-store buildings

	CS-1			CS-2		
	Embodied energy (GJ)	Annual allocation (GJ yr^{-1})	Crop attribution (MJ kg^{-1})	Embodied energy (GJ)	Annual allocation (GJ yr^{-1})	Crop attribution (MJ kg^{-1})
Wall Insulation	6231-11563	249-463		997-1850	40-74	
Roof Insulation	20693-38303	828-1532		1475-2730	59-109	
Floor Insulation	19528-33575	781-1343		1392-2393	56-96	
Structure	981	39		70	3	
Total	47433-84422	1897-3377	0.047 - 0.084	4917-8804	197-352	0.013 – 0.023

The embodied energy values were allocated over a life span of 25 years. The CS-2 allocation and attribution values were adjusted for fruit storage at a leased site. (see Sect.3.3.5 for method).

uncertainty (U2) existed for CS-1 in that some of its own cool-stores were leased out for chilled or frozen storage during the 'off season' period, and even during the export season. To allow this level of flexibility, the construction specifications of some storage rooms exceeded the insulation and plant requirements needed for chilled fruit storage. Fruit was only attributed the indirect energy cost of its own requirements (buildings in which fruit was actually stored, and appropriate insulation requirements).   However, direct cooling energy costs could not be correctly allocated where the plant served several buildings. For CS-2, the uncertainties tended to cancel each other out but the net effect was not determined. The two case studies were selected specifically to minimise uncertainties such as these, but even so they appeared to be unavoidable, particularly for larger organisations such as CS-2. U1 resulted in an under-estimation of both direct and indirect energy attributable to the crop, while U2 resulted in an over-estimation, because energy that should have been attributed to another product (or another organisation's product) was attributed to this crop.

4.2.9 Apple packaging energy content

A wide range of values for wood-fibre packaging have been reported. Previous work and the methodology for the present study are discussed in Sect. 3.4, while further implications are discussed in Sect. 4.5. Blanke and Burdick (2005) attributed 0.65 MJ kg^{-1} of primary energy for packaging to New Zealand apples.   A higher value (1.46 MJ kg^{-1}) was calculated as the benchmark for a standard z-pack (Tables 21, 23).

A summary (Table 22) of the energy intensity (MJ kg^{-1}) of post-harvest processes in the New Zealand apple production and supply chain to Northern Hemisphere destination ports reveals direct and indirect shipping to be the most significant contributions, followed by direct refrigeration energy. A combined farm and post-harvest summary is presented in Sect. 5.1.

Table 21: Energy content of standard apple pallet materials

Component	Mass (kg)	Energy content (MJ)	Energy content per pallet (MJ)	Energy intensity (MJ kg^{-1})	Attribution to apples (MJ kg^{-1})
standard z-pack	1.2	14.4	806	12	
pallet	20	528	528	26.4	
fibre trays	0.45	3.24	181	7.2	
Totals		546	1516	45.6	1.46

4.2.10 Shipping results and discussion

The energy attributable to apples shipped to various export markets was calculated from a study of container ships (n = 49). The methodology is summarised in Sect 3.1.2. The mean direct energy consumption of apples calculated was 0.27 MJ t^{-1} km^{-1} (range 0.17 MJ t^{-1} km^{-1} to 0.32 MJ t^{-1} km^{-1}).

A useful reference point has been reported for the actual fuel consumption of MSC Pamela. The value reported (248 tonnes per day) was 10% less than the calculated value (271 tonnes per day). The container vessel MSC Pamela value is widely

Table 22: Post-harvest process energy intensity summary table

Components of post-harvest energy	Total embodied energy (MJ kg^{-1})		
	CS-1	CS-2	Mean
Shipping direct	2.59	2.59	2.59
Shipping indirect	1.54	1.54	1.54
Direct cooling (electricity)	0.52	0.12	0.32
Direct packing / administration	0.03	0.09	0.06
NZ land transport	0.054	0.04	0.047
Direct lift-trucks	0.06	0.03	0.045
Indirect cool-store buildings and	0.07	0.02	0.045
Direct waxing	0	0.041	
Indirect packhouse plant	0.008	0.009	0.0085
Indirect refrigeration plant	0.0062	0.0056	0.0059
Indirect lift-trucks	0.0053	0.0061	0.0057
Indirect -packhouse and sundry	0.004	0.00014	0.00027

Table 23: Energy attributable to apples in common pallet configurations

18.5kg cartons per pallet	Apple weight (kg per pallet)	Energy Content
49	906.5	1.54 MJ kg-1
56	1036	1.46 MJ kg-1

reported as an example of notable fuel efficiency[33] so it is reasonable to expect the calculated value to be higher. In a personal communication a shipping company representative provided further indicative reference values[34] for fuel consumption:

- Bulk reefer vessels   75 gms fuel TEU^{-1} km^{-1}

- Container vessel   39 gms fuel TEU^{-1} km^{-1}

---

[33] http://www.ships-info.info/mer-MSC-Pamela.htm
[34] TEU = twenty foot equivalent container unit

Energy usage for containerised refrigerated freight, and total payload energy usage for representative trade routes (Table 4.5) were calculated through the methodology described in Sect. 3.5. A comparison of the value calculated (0.27 MJ t^{-1} km^{-1}) with the value of 0.23 MJ t^{-1} km^{-1} reported by Webb (2004) for bulk freight, implies that modern reefer vessels can transport refrigerated freight for an energy cost only slightly higher than that of mixed freight in Australian coastal trade.

The values calculated (Table 24) suggest a higher differential between refrigerated and average freight (average freight was 66% of refrigerated freight). However, the value reported by Webb (2004) can be assumed to take into account smaller and older vessels than those used for refrigerated shipping, while the move to integral refrigerated containers (Wild, 1995) requires reefer vessels currently in use to be either relatively modern or refitted. It is quite reasonable to conclude that modern container ships are more energy efficient than a broader, older range of freight vessels. The value 0.27 MJ t^{-1} km^{-1} was specific to refrigerated apple freight.

Table 24: Refrigerated freight energy consumption for specific apple routes

From-to	Distance (km)	Days at 22.7 kts	Reefer MJ kg^{-1}	Fuel (t)	Fuel t TEU^{-1}	Payload GJ TEU^{-1}	Payload direct MJ kg^{-1}	Payload indirect MJ kg^{-1}	Payload MJ kg^{-1}
Nelson Felixstowe	24700	24.4	6.67	4,579	0.74	30.89	2.84	1.69	4.53
Napier Felixstowe	26250	26.0	7.09	4,866	0.79	32.83	3.02	1.79	4.81
Nelson Rotterdam	24900	24.6	6.72	4,616	0.75	31.14	2.86	1.70	4.56
Napier Rotterdam	26500	26.2	7.16	4,912	0.80	33.15	3.05	1.81	4.86
Nelson Philadelphia	18400	18.2	4.97	3,411	0.55	23.01	2.12	1.26	3.37
Wellington Philadelphia	17800	17.6	4.81	3,300	0.54	22.26	2.05	1.22	3.26

Column 4 'Reefer MJ kg^{-1}' is the product of the route distance and the calculated energy consumption reported above. This value incorporates the calculation of refrigeration energy. The fuel usage and the attributed energy were based on the mean consumption of the 49 vessels (for methodology, see Sect. 3.5). The range within the vessels is from minus 37% to plus 19% of these values. Column 10 'Payload MJ kg^{-1}' presents energy usage for average freight. (see Sect. 3.5.3.1)

A broad relationship exists between the size of vessels and the energy efficiency. Hull speed is regarded as a function of the square root of the waterline length (LWL). A unitless version (the Froud number) is expressed as $Fr = V\,c^{-1}$. The rated cruising speed of the sample group was measured as a function of the square root of the overall length (LOA) (Fig. 26). This relationship has a subsequent influence on refrigerated cargo, since although the energy consumption of reefer containers is independent of vessel size, a shorter voyage requires less shipboard cooling energy. The selection of vessels for this study was deliberately biased towards larger, faster vessels (see Sect.2.2), arguably resulting in a lower energy usage value than would have been achieved from a random cross section of the global container fleet.
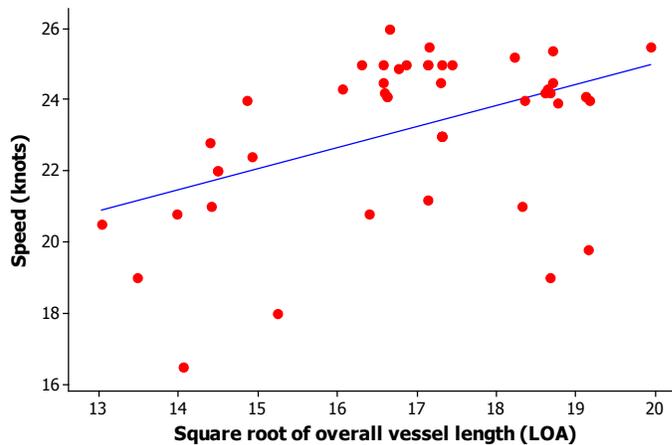
Figure 26: The relationship between sample group vessel length and cruising speed. Speed (knots) = 13.18 + 0.59 Square root LOA, p = 0.001 (App. III.IX, p230)

The lower observations are underpowered, and could potentially operate at a higher cruising speed limited by the established relationship between vessel length and cruising speed.

The relationship between refrigerated shipping transport energy and vessel size and speed was calculated via a regression equation (App. VI, Fig. A 6.1, p253):

total reefer[35] energy usage (MJ t^{-1} km^{-1}) = 0.139 + 4.43 power GT^{-1} speed^{-1}

where:

---

[35] The term "reefer" is used to describe both refrigerated vessels, and refrigerated containers

- power is the rated power of the main engines measured in kW

- GT is gross tonnage

- speed is the maximum cruising speed measured in knots

4.2.10.1 Shipping refrigerated apples - discussion

A further discussion impinges here, as to the relationship between containerised refrigeration and land-based refrigeration. The purpose of the industrial processes of fruit refrigeration is to meet customer demand for year round supply of a seasonal product. Apples are a fruit of temperate regions, so harvest is limited to mid-latitude Northern and Southern Hemisphere autumns[36]. Customer demand for products outside of seasonal constraints requires the natural gradient of deterioration (following harvest) to be managed through various technologies, whether or not the product is transported. Therefore in assessing the impact of the refrigeration component of transport, it is not only the absolute energy requirement that is significant, but also the difference between refrigerated containers and land-based refrigeration. Energy inputs extend from harvest to consumption, so the energy content of a particular product is a function of time from harvest as much as distance.

4.2.10.2 Strategic implications for the New Zealand apple industry

Marine transport comprises the largest energy component of the apple supply value chain prior to the destination port. Notwithstanding the finding that domestic transport energy inputs between supermarket and consumption may be of the same order (Browne *et al.*, 2008), any mechanism for reducing shipping transport energy costs (and associated emissions) should be leveraged. Buhaug *et al*. (2009) p 13, reported potential reductions in shipping emissions from 25% to 75% through technological and operational interventions.

A direction indicated by this preliminary investigation is to investigate strategies that promote, attract or enable the use of the most efficient container vessels in the global fleet, and conversely restrict the use of older inefficient vessels for the freight of New Zealand pipfruit. An associated mechanism is for New Zealand to engage academically with international research in the marine emissions reduction field, and

---

[36] Austin and Hall (2001) described the climatic requirements of apple production.

to engage politically with the marine emissions reduction process. The potential energy and emissions reductions in this aspect of global food delivery outweigh the improvement potential by intervention in any other aspect of the New Zealand apple production process.

4.2.11 Summary of results for the experimental component

A theme of the farm level results was that most farm-level energy inputs were linked directly or indirectly to pest and disease management processes. Although the data measured in this study was not intended to provide detailed information at the farm process level, the link to crop spraying could be inferred through recorded chemical applications and inventories of orchard equipment. The largest component of these inputs was direct fuel usage, while capital and agrichemical inputs were also significant. The energy content of fertiliser was closely comparable to capital and agrichemical inputs, although the nature of uncertainties was different in each case. An unanticipated result was that the OFP cases could not be statistically distinguished from the IFP cases for any input other than the indirect energy, and similarly the intensive cases could not be separated from the conventional cases.

The most significant components of post-harvest energy usage were shipping and packaging. Onshore post-harvest processes were found to be relatively energy-efficient, including onshore transport energy costs, which were surprisingly low. There was a substantial difference between the energy inputs of the two post-harvest case studies for both indirect and direct coolstore and packing processes, indicating both case specificity, and potential for improvement.

4.3 Philosophical and systemic issues in LCA

4.3.1 Introduction

Life cycle assessment (LCA) is a method closely supported by a philosophy (life cycle thinking) and a wider management approach (life cycle management). In this discussion the abbreviation LCA is taken to incorporate all three aspects. Curran (1993) provided a short history and description of LCA. She described LCA as (p 1):

"an holistic approach that analyses the entire system around a particular product."

The two descriptors 'holistic' and 'systemic'[37] occur frequently in discussions of the emergence of LCA as a dominant framework for environmental assessment.

However, while the generic term 'holistic' can be argued to be valid for LCA, claims that it is a systemic framework are challenged. Ulrich (1993) addressed the issue of ecological studies claiming a more complete knowledge than they are entitled to, and recommended critical systems heuristics (CSH) as a resolution (Sect. 2.7.1.3).

LCA has been represented as providing a basis for substantive improvement rather than tradeoffs with no net gain. Curran (1993, p 432) provided an example of how LCA could provide a more complete viewpoint, and avoid an illegitimate tradeoff:

"…an apparent improvement to a product that decreases air pollutants but results in increased water borne pollutants could be identified by an LCA."

This example encapsulates the strength of the LCA method. It enables pragmatic and rigorous measurement of the environmental impacts within a defined set of boundaries. Guinée *et al.* (2002) provided practitioners and theorists with a comprehensive overview of the history and practice of LCA up to that point.

---

[37] See Sect. 2.7 for a review and discussion of systems concepts.

4.3.2 The linearity of LCA

The term 'product life cycle' incorporates manufacturing, usage and disposal impacts, as well as factoring in downstream and upstream effects. However, the approach is a reductionist scientific approach in that it reduces a system to the sum of its components, albeit from cradle to grave, and notwithstanding that the analyst is required to look for marginal implications. The LCA process is linear, and the methodology has not yet been rigorously integrated with an iterative or cyclic intervention methodology. An assumption implied in the LCA method is that to get a good result the core requirement is good data, and that good data will be a basis for good decision making. The converse - that bad data may result in bad decisions - is certainly true, but while good data are a prerequisite for sound decision making, they do not guarantee it. With respect to linearity, both the process and input-output approaches assume linear flows of energy and matter, leading to a linear problem solving mind-set. The linear approach is fundamentally flawed as a basis for understanding sustainability. Hjorth and Bagheri (2005, p 83) wrote:

"environmental policy cannot be shaped around an idealised linear path of gathering and subsequent application of scientific knowledge."

Philosophers of science were shown (Sect. 2.6) to strongly support a world view that is complex and interconnected, so while it is clear that while LCA has proven a useful tool for measuring the inputs and emissions associated with products or processes, its assumptions fail to reflect the complexity of reality. The logical conclusion is that LCA should be rigorously associated with a larger set of methods that do in fact recognise and reflect the complex interactions of systems.

4.3.3 The need to recognise emergence

Systems thinking recognises not only the component properties, but also emergent properties. Lovelock (1989) equated 'top-down' input-output analysis methodology with 'systemic analysis', and indeed a top-down approach is capable of including some emergent properties of a system. For example, the farm-level component (Sect. 3.2.1) of my study measured direct and indirect energy usage from a top-down

perspective[38]. In Sect. 3.2.1 the direct energy usage was measured as total farm consumption rather than generated from process data. In a very limited sense direct energy usage could be considered an emergent property. The processes consuming the energy were treated as a 'black box', and the interactions between farm processes were generally ignored. However, emergence is a much richer concept than just the performance outcomes of a process, potentially extending well beyond the boundaries defined as the 'top' of a top-down frame of reference. Emergence is not limited to just the energy and material flows observable in the system components. For example, the emergent properties of motor vehicles have impacted the entire physical, cultural, social and political environment of modern civilisation.

Some systems are exceedingly complex, and "cannot be described in any precise or detailed fashion" (Jackson, 2000). This author went on to explain the black box concept, which rather than attempting to understand the complex workings and possible states of a system, limits itself to "manipulating inputs and classifying outputs". Farming systems conform to the characteristics described by Jackson (2000), demonstrating a high level of diverse interactions, including connections with the market and the environment. The resulting outputs are further complicated by site-specific management practices (Mila` i Canals and Clemente Polo, 2003). In my study, each orchard was observed to consume energy in an environment, via a set of activities, and with processes and technology that were similar but never identical to other orchards. Nevertheless, the resulting fuel consumption was observed to conform to a statistical distribution. The resulting energy usage indicators (reported in Sect. 3.2.1) were claimed, following Ulrich (2001, p 17) to be:

- valid - the observations measured what they were supposed to measure

- reliable - the observations could be repeated over time and provide a statistically stable result

- transferable - observer independent

- relevant - the observations provided information that served as support for an argument

---

[38] In Sect. 3.1.1 the term "downward looking" was argued to be preferable to "top-down", because "top-down" implied that a real upper limit was definable, when it was demonstrably not.

4.3.4 Value-rich imbedded tacit knowledge

However, despite a level of safety in those results, when the results were compared to results from similar studies in other systems in Sect. 3.2.1 the issues of tacit knowledge imbedded in the assumptions and boundary decisions could potentially have compromised those comparisons. This was most readily observed in the methodology for assigning energy content to packaging.

A further example is provided to show how knowledge that can be articulated exists in a larger matrix of knowledge that is much more difficult to articulate (Polanyi, 1966). Many of the indicators in Sect.3.2.1 were reported as a function of land area (e.g. GJ ha^{-1}). In New Zealand, concepts of land tenure have been challenged and revised in relation to the Treaty of Waitangi signed in 1840 by indigenous Maori chiefs and the British Crown (King, 2003). Specific ownership has been challenged, and restoration made to redress historical injustices. In many cases, the language used in early negotiations failed to bridge the difference in world-view between the cultures.

The point here is that the measurement of an apparently value-free entity such as land area incorporates value judgments at a deep level that may or may not impinge on the ability or right of a producer to farm that land sustainably. The customer may or may not be concerned about these issues, and may or may not be judged to have any right to make decisions based on them. Many New Zealanders are proud of the level of engagement and redress achieved with the indigenous population, and would count these achievements as a positive attribute embodied in measurements of land, while many others are aggrieved and seek further redress (King, 2003).

A further understanding of value-rich knowledge imbedded in land area in the New Zealand context would incorporate the regulatory environment in which that land is sited. This would include the management of water resources and the management of catchments, including forested conservation estate protecting those water resources. An area of land in New Zealand cannot be dissociated from its context - a context that is largely unknown to researchers outside New Zealand. Other producer states and regions have historical, social and environmental issues, and cultural presuppositions

that should be regarded as normative knowledge imbedded in indicators reported as a function of land area.

Information such as this would necessarily be excluded from the boundaries of an LCA study even though it might be of vital significance to at least one stakeholder group. The LCA practitioner has no means by which normative knowledge of this nature might be incorporated into findings. This knowledge would not prevent the researcher from forming assessments that are valid, reliable, transferable and relevant, but it would impinge on comparisons and interventions ensuing from the life cycle assessment.

If a black box methodology (Sect. 2.7.2.1) were adopted, factors within the black box might contain tacit knowledge that could impinge on the meaning of observations, as well as impinging on tacit judgments embodied in the boundaries of the black box, and normative judgments implicit in the inclusion and exclusion of inputs and outputs. While a top-down analysis addresses some requirements of systems thinking, it fails to address others at precisely the same points as a process analysis.

Therefore it is argued that the LCA approach is an invaluable, primary mechanism for informing a systemic investigation, but it does not in itself constitute a systemic analytical framework. Both forms of study are necessary, but LCA is a linear, positivistic approach rather than an holistic systemic approach.

4.3.5 Software modelling approaches – limitations and opportunities

It is self-evident that software relying on logical computations is not capable of forming value judgments. Anecdotal evidence of the positivistic nature of the LCA approach is the trend toward the use of software to facilitate the linear accounting computations required for an LCA (Rice *et al.*, 1997).

Development of the system dynamics (SD) methodology (Forrester, 1968; Hjoth and Bagheri, 2006) has taken some account of human soft system elements by integrating system influences that incorporate soft system elements (such as human values) in system behaviour. Attempting to model complex systems that incorporate both

positivistic and normativistic (Sect. 2.7.1) knowledge has attendant risks, as the modeller only ever has access to part of the information. However, it is preferable to attempt to model the possible states of a system than to make interventions based only on positivistic knowledge such as sustainability indicators. Therefore the SD methodology is proposed as an important component of a holistic life cycle model.

4.3.6 The tacit assumptions of LCA

A thesis of the present work is that both numerical indicators and scientific methods inevitably contain tacit, imbedded assumptions. In the case of methods, those imbedded assumptions may impinge on the meaning of the results of LCA studies, or their application in a specific context.

4.3.6.1 Assumptions derived from the history of LCA

I previously examined the historical development of the industrial approach of lean thinking in order to reveal hidden assumptions (Frater and Houston, 2008). Adopting this pattern, historical reviews (Curran, 1993, Hunt and Franklin, 1996) reported that LCA had its beginnings in the 1960s, amidst concerns over decreasing availability of raw materials and energy resources. A 1969 study for the Coca-Cola company was regarded by both authors as a foundational LCA study. The early US architects of LCA were associated with Coca-Cola and the economics and management science division of the Midwest Research Institute (MRI). The fuel crisis of the 1970s prompted further studies, while in the latter half of the 1980s the focus moved toward environmental emissions. The method itself was refined into a process beginning with the definition of system boundaries, and progressing through (life cycle) inventory construction, impact assessment and improvement analysis. Curren (1993) emphasised the need for practitioners to clearly state their assumptions. She also required published results to be subject to a peer review process.

If, following Polanyi (1966), knowledge that can be articulated depends on a bank of knowledge that cannot be articulated, then we can argue that there would be benefit in surfacing as much unarticulated knowledge as is possible. In the case of lean thinking, Frater and Houston (2008) found a number of assumptions imbedded in the methodology that ensued from its roots in the industrial discipline of quality, and

more specifically its maturation in post-war Japanese industry (Sect. 4.3.2). Following that case, we can enquire whether LCA's roots in the growing environmental awareness of the 1960s and 1970s affected the evolution of the method in ways that are no longer obvious?

Notwithstanding similar lines of development were occurring simultaneously in Europe (Hunt and Franklin, 1996), the genesis of LCA in a multinational US corporation had inevitable consequences for the assumptions of the LCA process. A certain level of synergy can be observed between the factors contributing to the production of a beverage (a food product, packaging, transport and disposal) and the whole life cycle approach. This synergy is best articulated by postulating what LCA might have become if it was conceived in a completely different environment (e.g. military, health or government, an ecologically focussed academic environment or an Eastern rather than Western country).

4.3.6.2 Assumptions derived from the context of LCA's genesis

The aspects of the LCA approach that are synergistic with its genesis are its apparent assumption that the result is the sum of the component parts, and its linearity. Another assumption than can be inferred from practice rather than theoretical underpinning, is that it is the scientist's task to discover information and relationships, but some other agent's responsibility to make decisions regarding change. This reflects a corporate mindset where a methodology would be assigned to lower organisational levels, and decisions (based on information provided) made by upper management. A further assumption is derived from the dualistic Western worldview described by Bohm (1980), where man is separate from his environment. That frame of reference was influenced by a Judaeo-Christian viewpoint of man's relationship with the environment. Judaeo-Christian attitudes to nature range from arrogant domination, through responsible husbandry to Franciscan humility (Schaeffer, 1970). LCA appears to have a middle-ground husbandry relationship as its presupposition.

In another case (Sect. 4.2.3), that of assessing the embodied energy of apple packaging, the author identified a change in emphasis (between the 1970s and the early 21st century) from energy shortages and resource depletion to climate change.

This change materially affected the validity of indicators constructed in the 1970s for use in the 21st century. The same is likely to be true of older data included in life cycle inventories, particularly if it is used as a basis for constructing new data.

However, the objective here is to surface assumptions that are imbedded in the methodology itself, rather than context-driven assumptions. LCA is fundamentally a framework for informing intervention. That is, the goal of gaining knowledge in the wider context of sustainability is to bring about purposeful change. In the case of agricultural, or food supply contexts, the scientist is therefore thrust into the role of the action researcher.

4.3.6.3 Assumptions derived from the practitioner's worldview

Herein lies an assumption that is imbedded in the methodology. The scientist may assume that observation and reporting of inventory data will not affect that data. Frater and Houston (2008) argued that the acts of observation and reporting of data constitute an intervention. LCA practice is the type of scientific enquiry in which the researcher is intimately connected to the subject being studied, and it is not difficult to postulate mechanisms by which the observer might materially affect the observed. An example in the present study was when a post-harvest manager (from CS-2) expressed an opinion that the researcher's interactions with them had been of material benefit, before any results were reported, and when those interactions were intended to be limited to questions and observations. Midgley (2003) argued that the observer actively constructs an observation. That is, an observation is a construct framed within the tacit worldview of the observer. He also argued that decisions about what is observed have moral implications. These arguments may appear pedantic or even trivial to the practitioner, but they are supported by the arguments proffered by philosophers of science including Polanyi (1966), Bohm (1980) and Popper (1972).

Tukker (2000) explored the role of positivism in science in the context of LCA. He argued (p178) that the positivistic view is the one that most "environmental specialists" proceed from, but that such a view was becoming increasing untenable in the light of Kuhnian relativism. A more proper view would accept the existence of multiple realities, realities that he defined in terms of alternate "frames".

4.3.6.4 Assumptions based on moral and ethical judgments

Some non-stated assumptions in an LCA investigation are likely then to hinge around moral and ethical value judgments made in the selection of the area to be studied, and the boundaries of the study. The arguments of Johnson (1984) -outlined in Sect.2.6.1 - demonstrate that any study of food products requires normative judgments to be made at the very earliest stages of the investigation. Lying beneath boundary decisions are judgments that may not even be known by the researcher, let alone understood. A second set of assumptions is likely to exist in the researcher's awareness (or lack of awareness) of connection with the observed. Practitioners are likely to view the inventory stage of LCA as a situation in which the researcher remains removed from the observed entity. The likely assumption is that any real effect on the system under observation will be limited to the purposeful change stage. The arguments of Bohm (1980) and further development by Midgley (2000, pp123-128) show that the observer cannot avoid influencing the observed.

Another example of the observer influencing the observed in the present research, was when the survey of energy usage was circulated to apple growers. The specific identification of urea as a potentially significant energy component may have resulted in growers becoming more cautious in its use.

A further danger for a practitioner of LCA is that they may assume that it is possible to know all the information relevant to a given system. Even a cursory examination of this assumption shows it to be untenable, and Ulrich (1993) soundly refutes it. Arguments pertaining to the need for an awareness of value judgments and ethical issues are made strongly by Midgley (2003) with respect to intervention in human systems.

This analysis is admittedly superficial, and relates only to a broad overview of the LCA methodology. A closer and more rigorous examination would undoubtedly reveal other assumptions. The point of this examination is not to conduct a rigorous enquiry, but rather to demonstrate the need for an approach that will take allow the practitioner to engage in genuinely holistic, systemic research.

The change that I propose is to integrate soft systems thinking with the existing LCA methodology, to provide that genuinely holistic framework for managing change so as to advance sustainability, firstly within food supply chains, and secondly within other complex global systems.

4.3.7 Sustainability indicators – a philosophy of science perspective

The core argument enunciated in the present study is that great care must be taken in building scientific knowledge in fields involving human activity. Such knowledge has been built from a changing viewpoint, and knowledge encapsulated in seemingly objective indicators has inevitably embodied the assumptions of observers. The argument questioned the assumption that numerical sustainability indicators constituted objective knowledge that could be used to build further knowledge, and to generate practical, socio-political strategies. While this procedure was not rejected per se, it is argued that the tacit assumptions embodied in sustainability indicators must be surfaced by systemic enquiry, so that they can be safely adapted to new environments.

The use of scientific methodology to explore the mechanisms and processes of food production is essential. However, at all points in the process, the scientist must be aware that he/she is working in a complex system, that the context and application of the science will be in a systemic environment, and that the research should be informed by the systems thinking body of knowledge.

4.3.7.1 The nature of scientific knowledge and objective truth

The philosophers of science have discussed the concepts of knowledge and truth at length. While there is no absolute consensus, their discussions have formed a basis for developing an understanding of the issues surrounding the present work. Popper (1972) discussed the notion of scientific objectivity. He described a process:

$P_1 > TT > EE > P_2$

Where P_1 is the starting problem, TT is the tentative theory, EE is error elimination and P_2 is the emergent problem situation. He placed problems before observations,

and described his resulting knowledge as a new problem situation. Popper (1972) offered his philosophical framework in the context of three "worlds or universes". The writer's first world consisted of physical objects or states, and his second world that of "states of consciousness", "mental states" or "behavioural dispositions to act". Concerning us here is his "third world", which contained "theoretical systems", "problem situations" and "critical arguments".

A rather obvious point taken from this explanation is that the generation of a numerical indicator as a 'condensation' of an amorphous problem situation represents only a restatement of the problem in different terms, not a movement from Popper's third world to his first or second worlds. The indicator remains an, albeit revised, problem situation.

Popper (1972) was concerned more with underpinning pure science than applied science. However, a clear warning could be deduced. He wrote (p165):

"…we always pick out our problem against a third world *background*. This background consists of at least a *language*, which always incorporates many theories in the very structure of its usages, …and of many other theoretical assumptions, unchallenged at least for the time being."

His "tree of knowledge" is useful in describing the manner in which science has built on prior discovery, even if the new discovery was phrased in terms of new problems and arguments. Our concern is for knowledge, or the application of knowledge, to new situations where the theoretical assumptions are so different from the "third world" of P_1, that the resulting P_2 is no longer safe. I therefore looked for appropriate methods to contest and surface the unchallenged assumptions that form the third world background.[39]

---

[39] It is not within the scope of the present discussion to engage in the debate between the Popperian and Kuhnian viewpoints, however the Popperian construction is more useful in informing the present discussion.

4.3.7.2 The role of indicators in sustainability research

The pattern of scientific publications in the field of sustainability is that studies are performed following a set methodology such as LCA. These studies generate a range of conclusions, frequently offering indicators as outputs (Wells, 2001, Barber, 2004b). Indicators reduce the field of study to a 'common currency', which can then form the basis for further study. Work is invariably peer-reviewed: a procedure that examines and endorses the process and methodology by which the outputs have been generated. This paradigmatic process appears to be something of a simplification of Popper's intention, with indicators assuming an authority closer to objective 'truth' than a 'new problem situation'.

4.3.7.3 The nature of assumptions – a philosophical viewpoint

A distinction is made here between the normal practice of stating known assumptions (a practice that was followed in Sect. 3.1 of this study), and the deeper level of assumptions that are a particular characteristic of (but not limited to) situations involving human activity. To examine this distinction, we can draw from other philosophical models.

Bohm (1980) offers a model of knowledge building as a process. His analogy of knowledge as vortices in a stream (p48) is useful in informing this discussion. If, adopting Bohm's analogy, a reported indicator is compared to a vortex formed by an obstruction in a stream, then it is logical to consider the entire process by which the article of knowledge (the vortex) was formed. The indicator can be understood as an artefact of the entirety of the conditions, environment and matter at that time. To extend the analogy further, the indicator could be compared to a photograph, or video of the vortex. That is, the indicator reflects some essential characteristics of the studied situation, but cannot contain its full richness.

The argument presented here is that sustainability indicators are artefacts of a great deal more knowledge than is known or understood by the observer. The method by which they are generated can be understood in terms of explicit knowing, but a great deal of the context of the observation, including the assumptions and presuppositions of the observer must be considered to be tacit (Polanyi, 1966). In the Bohm (1980)

analogy, this tacit dimension can be compared to the hydrology of the stream, and the environment beyond it.

Polanyi (1958) explained that the tacit component of knowledge is the predominant factor in human understanding, rather than the explicit component. He wrote (p25):

"Our whole articulate equipment turns out to be a tool-box, a supremely effective instrument for deploying our inarticulate faculties. And we need not hesitate then to conclude that the tacit personal coefficient of knowledge predominates also in the domain of explicit knowledge and represents therefore at all levels man's ultimate faculty for acquiring and holding knowledge."

An analogy Polanyi (1958) offered is that of a map. The map, like literature or mathematical formulae represents an explicit representation of previous experience. However, the map holds no meaning in itself – it only takes on meaning when it is interpreted by a person with sufficient skill to use it to assist their travel. In the map analogy, the map takes on the role of the science established by previous researchers. The traveller is the observer, or the researcher seeking to extend or apply the science at a later date.

4.3.7.4 An extension of the map metaphor

The use of analogies and metaphors is a recognised tool in both the philosophy of science (Montushi, 2001) and systems thinking (Flood and Jackson, 1991), and while a metaphor cannot constitute a proof, it serves to bridge gaps between physical science and the mental structures we use to comprehend that science.

An example from my personal experience is offered to extend the analogy into the current context. I have experienced wilderness travel before the advent of GPS technology. In using a map to traverse wilderness, the issue is usually not whether the map is in fact accurate, but where the traveller is in relation to the map. In one instance, a topographical map represented the existence of a tributary stream, marking the point at which the route departed from a valley and climbed to a ridge. On the occasion when my party reached this junction, there was no water flowing, and the

small indent didn't appear to match the scale of the tributary stream marked on the map. The party mistakenly moved on into much more difficult terrain, incurring delays and injuries. This example demonstrates that the tacit knowledge imbedded in the map ('there is usually water flowing in this tributary') didn't match the tacit knowledge of the party. In this instance, a small deviation between the tacit knowledge of the initial observers, their interpretation and subsequent publication of explicit knowledge (the map), and the tacit knowledge of the party resulted in a significant error.

In the example above, the only environmental change was the passage of seasons. The map represented normal or average conditions, while the party travelled in a dry summer. In the scientific situation under examination in the present study, the context is a field of research in which the global frame of reference has evolved substantially over several decades. In this instance it is highly likely that the tacit knowledge of earlier researchers will differ at many points from the tacit knowledge of persons interpreting the explicit knowledge generated by earlier research.

4.3.7.5 Conclusions of arguments regarding sustainability indicators

With respect to sustainability indicators, our response must be to ratify their deployment as a basis for future science, or economic and political policy. We should adopt or develop methodologies to surface the hidden assumptions of both the earlier researchers, and the later adopters of that research.

4.4 LCA methodology –a proposed development

4.4.1 Moving to a more holistic framework for LCA studies

Four areas of knowledge emanating from systems research, but neglected in current LCA practice, are presented below. They are integrated with LCA in Table 27, and proposed as an holistic approach to purposeful change:

1. Soft systems investigation:
The identification of normativistic knowledge, such as moral value judgments, or unresolved ethical questions associated with the proposed boundaries of a study.

The surfacing of tacit knowledge imbedded in life cycle inventory (LCI) data.
The identification of the frame of reference from which inventory data was
constructed, and rigorous comparison with the frame of reference of the current study.

2. The investigation of causative relationships, including those between normativistic
and positivistic data

3. The modelling of possible system states

4. Systemic principles for intervention and change management

4.4.2 Critical System Heuristics – An approach for surfacing and resolving soft systems issues within LCA

Midgely (1997) advocated Werner Ulrich's critical systems heuristics principally as a
mechanism for dealing with coercive situations, but he reported its adoption in a much
broader range of applications. In the context of my research they might be adopted at
the early stages of LCA; that is during product definition and boundary selection, and
in the proposal of interventions. The 12 critically heuristic boundary questions
(applied in two modes – either "is or ought") form an explorative framework that is
capable of revealing hidden assumptions. They perform the invaluable function of
bridging the gap between scientific 'hard systems thinking' and 'soft systems
thinking', a domain that is associated with social sciences (Vidal, 2006).

The argument made here is that from the early stages of an LCA study, the scientist is
engaged in action research, and cannot assume separation from the system under
study, or freedom from normative, ethical or moral judgments. Competence is
required in the tools of ethics and boundary construction (Ulrich, 1987, Ulrich, 2001,
Ulrich, 2002a, Ulrich, 2002b, Ulrich, 2000). The researcher is required (Ulrich, 2000,
p 252) to consider an "eternal triangle" or "argumentative triangle" of facts, values
and boundary judgments. These are interdependent rather than discrete, and altering
one will inevitably impinge on the others.

The CSH approach interrogates a proposal in terms of facts and values that are
presently included (the 'is' mode), and facts and values that are presently excluded
(the 'ought' mode). If these four aspects are not handled "in an open and transparent"
way, then ensuing claims are neither clear nor valid (Ulrich, 2005). The first of two

summary tables provided by (Ulrich, 1987) that clarify the CSH approach is presented in Table 25:

Table 25: Four perspectives for examining selectivity

	Empirical selectivity perspectives ('Is' mode)	Normative selectivity perspectives ('Ought' mode)
'Facts'	Actual mapping: What 'facts' are considered relevant and which ones are left out?	Ideal mapping: What 'facts' ought to be considered relevant and which ones should be left out?
'Values'	Actual mapping: What 'values' are considered relevant and which ones are left out?	Ideal mapping: What 'values' ought to be considered relevant and which ones should be left out?

Reprinted from Ulrich (2005, p 8) – generic permission to reproduce

Utilising this method to surface the assumptions of an LCA analysis constitutes an extension of the approach beyond its original context. In the context of an agricultural LCA study, a further refinement of the some of the questions is proposed:

Sources of motivation

Who are (ought to be) the beneficiaries of the system under examination?

1.a Who enjoys (ought to enjoy) the benefits of the agricultural product being produced?

1.b Who receives payment (ought to receive payment) for producing and supplying the product?

Who suffers (ought to suffer) any negative consequences of the system under examination?

2.a Who is (ought to be) deprived of the raw materials that support the production of the product?

2.b Whose environment receives (whose environment ought to receive) the emissions of the production and supply system?

The use of the word 'ought' does not necessarily imply a common morality or worldview. It does however require the acknowledgement of a worldview. The 'ought' components of these questions are demonstrably normative, ethically and morally challenging questions. The adoption of the CSH approach would inform the scientist of normative assumptions that might otherwise remain tacit. They would potentially prove useful at the boundary construction stage of LCA, but are proposed as an approach to gathering normativistic information, separate from, and parallel with the life cycle inventory (LCI) stage. However, normativistic information is unique to a particular system, so it cannot be assumed that information gathered for one system would be valid for another. Therefore it cannot be gathered and stored in a form similar to an LCI database, but must be assessed for each new application.

4.4.2.1 The question of non-human ethics

The normative issues explored above are essentially anthropocentric. However under "sources of limitation" (Table 26), Ulrich (2002b) questions who speaks for (and should speak for) non-human nature. The discipline of environmental ethics distinguishes between instrumental value and intrinsic value (Jamieson, 2002). The question inferred here is whether non-human nature has intrinsic value, and what is the extent of that value.

A philosophy exists that assigns aspects of morality to living things, to environments and even to the earth itself irrespective of human perspectives (Rolston, 1975, Routley, 1973, Schaeffer, 1970, Stone, 1972). Since food production systems impinge on the physical environment, our critically heuristic questions should explore non-human ethics. An expansion of the sources of legitimation to include these could include:
- Which elements of biodiversity are affected (should be affected). Is it morally right to allow a producer enterprise or state to make decisions regarding consequences in their immediate environment? Is it morally right for consuming enterprises or states to make decisions regarding consequences outside of their immediate environment?

- Which elements of biodiversity benefit (should benefit) from the system being investigated?
- Are we exchanging (should we exchange) good in one ecosystem for harm in another?

A further question arose in the development of this approach, as to whether CSH should be applied retrospectively in the examination of indicators produced in previous decades. The older a particular indicator is, the more likely it is to have tacit presuppositions that are inconsistent with the evolution of thinking around sustainability. The packaging example (developed in Sect. 4.5.2) shows that while early data are still useful, they may have to be reconstituted to fit present assumptions.

Early in this study, an anomaly was described where scientists performing rigorous peer reviewed studies achieved results that seemed to support the points of view of stakeholders with whom they were most closely aligned. The approach outlined above is proposed as a way to resolve these anomalies within LCA studies of agricultural systems, specifically where the anomalies are centred around tacit assumptions, or normative judgments imbedded in boundary decisions.

4.4.3 Total Life Cycle Intervention - a proposed methodological development of LCA

A proposed development of LCA methodology (Table 26) has five components. This methodology is intended primarily for the context of food supply chains, which were found to contain significant normativistic influences. TLCI is a combination of linear and cyclic, iterative and dynamic components. Component 1 precedes components 3 and 2 precedes 4 (Fig. 25). Component 4 is constructed from a synthesis of components 2 and 3. However component 5 is overarching, and while purposeful intervention must be preceded by components 1-4, the philosophy of systemic intervention underpins and informs all previous stages. The SD method is dynamic, but interventions must be monitored in a cyclic and iterative manner. That is, the real effect of interventions must be compared to modelled states, and the SD model developed in response. The iterative modelling of possible system states is informed by the systemic intervention approach (Fig. 27).

Table 26: The critical systems heuristics 'checklist'

Sources of motivation
(1) Who is (ought to be) the client or beneficiary? That is, whose interests are (should be) served?
(2) What is (ought to be) the purpose? That is, what are (should be) the consequences?
(3) What is (ought to be) the measure of improvement or measure of success? That is, how can (should) we determine that the consequences, taken together, constitute an improvement?
Sources of power
(4) Who is (ought to be) the decision-maker? That is, who is (should be) in a position to change the measure of improvement?
(5) What resources and other conditions of success are (ought to be) controlled by the decision-maker? That is, what conditions of success can (should) those involved control?
(6) What conditions of success are (ought to be) part of the decision environment? That is, what conditions can (should) the decision-maker not control (e.g. from the viewpoint
Sources of knowledge
(7) Who is (ought to be) considered a professional or further expert? That is, who is (should be) involved as competent provider of experience and expertise?
(8) What kind expertise is (ought to be) consulted? That is, what counts (should count) as relevant knowledge?
(9) What or who is (ought to be) assumed to be the guarantor of success? That is, where do (should) those involved seek some guarantee that improvement will be achieved – for example, consensus among experts, the involvement of stakeholders, the experience and intuition of those involved, political support?
Sources of Legitimation
10) Who is (ought to be) witness to the interests of those affected but not involved? That is, who is (should be) treated as a legitimate stakeholder, and who argues (should argue) the case of those stakeholders who cannot speak for themselves, including future generations and non-human nature?
(11) What secures (ought to secure) the emancipation of those affected from the premises and promises of those involved? That is, where does (should) legitimacy lie?

Reprinted from Ulrich (2005, p 11) – generic permission to reproduce. Originally in Ulrich (1987).

Table 27: Total life cycle intervention (TLCI)

	Component name	Stage description	Method(s)
1	Positivistic information gathering	The measurement of material and energy flows with respect to processes	LCI
2	Normativistic information gathering	The identification of value-rich assumptions, and tacit knowledge imbedded in information sources	CSH SAST
3	Linear modelling	Assignment of scale and values to positivistic information	LCA
4	Systemic modelling	The identification of key drivers and causal loops Modelling of influences combining positivistic and normativistic knowledge	CLD AD / ID SD
5	System management	The purposeful change of the system to enhance sustainability objectives	Systemic intervention
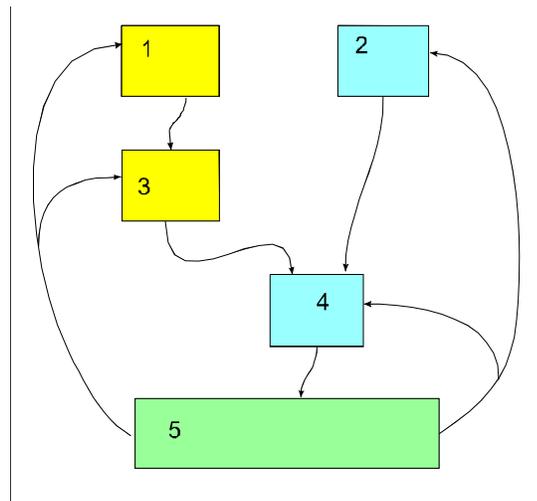
Figure 27: The relationships between TLCI components

Table 28: Details of TLCI components

	Component	Method / approach	Description or chapter reference	Reference
1	LCI	Life cycle inventory	Components of life cycle management	(Guinée *et al.* 1993)
3	LCA	Life cycle assessment		
2	CSH	Critical system heuristics	Chs. 2.7.1.3; 4.4.2	(Ulrich, 2002b)
2	SAST	Strategic assumption surfacing and testing	App. XII	(Mitroff and Emshoff, 1979)
4	CLD	Causal loop diagrams	Sect. 2.7.1.1	(Goodman, 1974)
4	AD	Affinity diagram	Components of the Seven Management and Planning Tools	(Brassard, 1996)
4	ID	Inter-relationship digraph		
4	SD	System dynamics	Sect. 2.7.1.1	(Forrester, 1968)
5		Systemic intervention	Sect. 2.7.1.3	(Midgley, 2000)

4.5 Discussion – methodological practices in energy studies

4.5.1 Introduction

The first part of this discussion examines the energy content of apple packaging materials (introduced in Sect. 3.4) as support for the thesis of this dissertation: that tacit presuppositions and boundary judgments materially affect the magnitude and the meaning of sustainability indicators. (Sect. 3.4.2. reports the use in this study of a value that was 29% less than the case it was derived from.) The second part considers the transfer of the industrial concept of lean thinking to environmental studies.

4.5.2 Issues identified in the energy content of apple packaging

Indicators derived from energy studies are typically reported as objective scientific measurements, and are consequently adopted by policy makers to inform the development of sustainability strategies. An examination of the assumptions underlying reported values has revealed a variety of value judgments and systemic presuppositions embedded in apparently objective reported numerical values. In order to gain a fuller understanding, the energy content of apple packaging was examined from a systems-thinking frame of reference. The objectives of the examination were:
- to provide further understanding of the complex relationships between contributing factors in energy and sustainability studies
- to develop understanding of the significance of embedded presuppositions in sustainability indicators
- to support the values adopted for apple packaging energy content in the present research.

Two established practices in energy studies were examined:
- accounting the exergy (the energy component that could be converted to useful work) contained in the biomass content of packaging as part of the embodied energy of that packaging.
- a related practice, whereby waste products from forestry used in the production process have been accounted in some studies as equivalent energy inputs to fossil fuel or electrical inputs.

4.5.2.1 The present context of energy studies

Energy studies have received unprecedented academic attention in the early 21st century climate of scientific and political thinking. The pressing issues were:
- rapidly increasing global demand for fossil fuel combined with a finite limit to the global resource (Chow *et al.*, 2003).
- general (although not universal) consensus among climate scientists that anthropogenic climate change was a real phenomenon (IPCC, 2007).

The foremost scientific objective in measuring the energy content of a product was to determine whether that product impacted negatively or positively on those critical

issues, and what the scale of those impacts was. In the context of the issues of climate change and fossil fuel depletion, measuring the energy content of packaging sought to establish the level of primary energy inputs and carbon emissions. Decades earlier, Boustead and Hancock (1981) took the position that since wood products were themselves a fuel, calorific energy content should be accounted as part of the energy "cost". Another commentator reported the inclusion of fuel energy in embodied energy indicators as common practice (Dalzell, 1999). Subsequent to the construction of this argument by Boustead and Hancock (1981), the issue of the depletion of fuel resources has intensified, and the issue of anthropogenic climate change has emerged.

4.5.2.2 Introduction to the philosophical difficulty

It is useful then to re-examine the arguments in the light of the urgency of current issues. While it may appear illogical and even unscientific to construct energy indicators to fit the social climate in which they will be interpreted, this can be argued to be normal and correct practice. Reported values will inevitably be applied to issues in the context of the current global (social, political, economic, geophysical and ecological) environment, so the assumptions embedded in the reported values must be synergistic with that context rather than an historical context.

The present context of energy and sustainability is framed in a complex web of interacting social and scientific assumptions. Sustainability indicators are constructed within the frame(s) of reference of scientists, and interpreted and applied within the frame(s) of reference of policy makers. The present research has identified circumstances in which these frames of reference have diverged in the period between initial research and subsequent research or political intervention.

4.5.2.3 Basis of the philosophical argument

The philosophical basis for this type of discussion follows the precepts of personal knowledge and tacit knowledge (Polanyi, 1958, Polanyi, 1966). These fundamental concepts of scientific philosophy demonstrate that when knowledge is represented as words, or even numbers, there are elements that are not able to be articulated. Even the most pure mathematical logic has a tacit component that is interpreted within the knowledge framework and experience of the observer. The concept has been

extended to knowledge building in organisations, Nonaka and Takeuchi (1995), described the success of Japanese companies in leveraging skills and intuition within the workforce that cannot be articulated in formal operating procedures or standards. This extension of the concept permits the proposed understanding of tacit knowledge in a collective sense, constituting the unarticulated knowledge of a group working in a particular field at a particular time. The tacit knowledge of concern is the unarticulated context of scientific endeavour and its application in global policy.

In the same manner that personal knowledge is framed within the experience and belief system of the individual, the collective knowledge of a group can be seen to be framed within the global context of that time, taking the form of an unarticulated common understanding. The personal or collective matrix of knowledge provides meaning to the inputs and outputs of scientific study.

Polanyi (1966, p6) explained that there is always more to a concept or a word than can be expressed. He described the transfer of knowledge from one person to another as concealing:

"a gap to be bridged by an intelligent effort on the part of the person to whom we want to tell what the word means".

The transfer of meaning across such a gap may be compromised where the meaning of a sustainability indicator formulated in a specific context differs from the meaning it takes on in the context in which it is applied. At least two distinct but interacting domains of information shape the frames of reference of groups of scientists or policy makers. The first is the current body of scientific knowledge, and the second is the background of global events, and consequent social and political pressures. These frames of reference can be argued to result in a set of presuppositions embedded in reported energy values and sustainability indicators. Another set of presuppositions underlies purposeful interventions or further scientific study. The frames of reference described here differ from the frames described in debates in LCA literature (Tukker, 2000). Those frames describe a mental model, or personal or collective attitude by which a researcher approaches research (see also Sect. 2.6.2).

In the case of further scientific exploration, a tension is identified here that stems from the fundamental practice of building scientific knowledge on the basis of precedence. This practice assumes safety in building knowledge on previously peer reviewed work, requiring the scientist to acknowledge prior work and defend any departure from it[40]. However, the context of my research demonstrates that in a rapidly moving field, the presuppositions embedded in earlier work may be significantly different from the context in which they will be interpreted, so that in some instances the safety of new knowledge is compromised.

In the issue of environmental sustainability and survival, the global context has evolved rapidly in the period 1980-2010. The indicator values generated in the context of the global circumstances of the 1980s can be seen to have a tacit or embedded content that could potentially make those values unsafe for application in the context of the early 21st century. This observation is unlikely to be a rare event, and is argued to expose a risk that indicates a need for a revision of the model of building scientific knowledge in rapidly evolving fields, particularly where that knowledge will be applied to global policy impacting on human sustainability.

4.5.3 The energy content of biomass in indicators – a key example

In the following discussion, the issue of the construction of energy indicators is examined with specific attention given to the energy content of biomass. The question underlying this examination was why scientific logic that appeared obvious and acceptable in the recent past should now be challenged, not necessarily because of new scientific knowledge but because of the global context in which the science might be applied.

4.5.3.1 Is biomass exergy harmful or beneficial? – an important distinction

The energy content of biomass is not primarily the result of human activity, neither does it conform to the general requirement that LCA inputs should be traced back to extraction of raw materials from the earth (Finnveden and Ostlund (1997). It has

---

[40] Sect. 2.6.2.1 offers a review of the scientific philosophies underpinning this paradigm.

resulted from the capture of solar energy through photosynthesis, a process that is modified by human activity in agriculture. The transformation of energy and sequestration of carbon through photosynthesis is a mitigating process with respect to climate change (IPCC, 2007) and is arguably neutral with respect to fossil fuel depletion. From this perspective it is counter-intuitive to include biomass exergy, or calorific content, in embodied energy indicators where they are to be applied to climate change arguments. To express the argument even more crudely, embodied energy indicators are interpreted as a deleterious component of production systems, while the energy content of biomass is either neutral or beneficial Biomass exergy is therefore argued to be an exception from the treatment of exergy consumption as a measure of resource depletion (Finnveden and Ostlund, 1997).

The value of wood products when used as an engineering material is a function of their mechanical properties, not their exergy. This argument is clearer in other primary products. In fruit production, the energy content of the fruit is just one component of several valued by the customer. Floriculture provides an extreme example, where the function of the product is typically aesthetic or biochemical, and the flower's exergy would be considered irrelevant. In comparison, where an energy crop such as sugar beet is grown for ethanol production, the obvious treatment is to compare the energy value of the crop with the energy inputs required to produce that crop. In the context of products other than deliberate energy products, the inclusion of the exergy of the products as a component of the embodied energy is argued to be incorrect. This practice certainly wasn't adopted in the apple production energy study (Sect.3.1), but it has been observed to be the default treatment in post-oil-crisis energy studies and the indicators derived from them (Boustead and Hancock, 1981, Dalzell, 1999).

The argument that appeared to underlie the inclusion of product exergy in embodied energy calculations hinged on whether the biomass could have been used more productively as an energy source elsewhere in the system. For example, the biomass could have been used to generate fuel as an alternative to fossil fuels. This is a fundamentally flawed argument, as a product is produced because society values it (whether packaging as in this discussion or some other product). Any suggestion that

the biomass would be better used as fuel than as a physical product is a value judgement that could be argued to challenge the validity of the free market model by which goods and services attract economic worth. Despite the apparently flawed logic behind the practice, the global context of the post 1970s energy crisis through to approximately the end of the 20th century supported that method of interpretation.

The reason is obvious in retrospect; the pressing need in that period was to determine energy flows through major industrial processes. Scientists and policy makers were more concerned with quantifying energy flows than determining environmental harm.

4.5.3.2 Energy from waste biomass

The inclusion of the energy recovered from waste biomass in aggregated energy usage is a separate related practice, which at first examination appeared quite logical. Here again the purpose of including the recovered energy component was to provide a complete picture of the energy consumed producing a product. This was clearly a useful metric, but it should not be confused with the impact of that product from a sustainability perspective.

Where a secondary forestry product is produced entirely from waste-streams, then there is no additional ecological burden other than emissions incurred by the process (that is, costs over and above those attributable to the primary product). From a sustainability perspective, the exergy of wood products has a positive component derived from the absorption of solar radiation, and a negative component derived from additional energy sources. The argument promulgated here is that energy inputs derived from "purchased" sources (including fossil fuels and electricity) should be accounted separately from the exergy of biomass feedstock. A more recent LCA study of packaging materials (Wiegard, 2001) excluded waste biomass consumed from the system inputs, and regarded this as the normal and logical treatment.

The global context of the last decades of the 20th century generated an overriding concern to know how much energy was required to produce a product or provide a service. The science was primarily concerned with identifying the components and their sources. The global context of current research (c 2010) is more concerned

about how environmentally harmful these energy sources are. Indicators generated from the earlier context should not be applied to the new context without consideration of changes in the frame of reference.

It is therefore argued that subtle change in global perceptions, albeit led and informed by scientific enquiry, can change the tacit knowledge providing meaning to sustainability indicators. This tacit knowledge should be rigorously surfaced, especially where indicators are offered as drivers of intervention, intervention that has been shown to be not limited to the actions of political agents, but an integral element of scientific observation (Midgley, 2003).

4.5.4 Accounting the exergy of waste-streams in sustainability indicators

The following section examines the treatment of the exergy of waste-streams, an area that was found to be inadequately understood and treated in energy accounting practice. The designation "waste-stream" is not a simple, precise or even necessarily useful concept. Industrial waste-streams are better regarded as co-product lines with inadequate or unidentified utility in terms of providing value to a customer. When a use is found for a waste-stream, it is no longer "waste". Waste-stream therefore is entirely a context-based descriptor. The nature of primary production is peculiar in that it is difficult to avoid co-products that incur more cost than they return. Manufacturers have comparative flexibility in their outputs. They can decide to reduce production in a certain product line, and increase production in another. Flexibility depends on the scale of production and the design of the production system. In comparison, a sheep farmer cannot easily decide to produce meat and not wool. The two products are intrinsically linked, and if one or the other incurs more cost than it returns it still cannot be put aside. The recovery of timber generates a volume of biomass that is not valued by the markets purchasing timber, and up till recently this biomass has been regarded as a waste-stream. However, the recent emergence of bio-oil processes offering valuable chemical products (Mohan *et al.*, 2005) has altered the perception of these products from a waste-stream to a feedstock.

The environmental accounting of the energy of a waste-stream can be examined in the context of the default destination of that waste-stream. In forestry, if the default is for bark and slash to be discarded to decompose naturally, then the energy derived from photosynthesis is lost to the environment and the carbon either returned to the atmosphere or partially sequestered in soil. Any production inputs (direct, indirect and capital energy inputs) or emissions can be attributed to the end product. Insofar as the emissions from the decomposition of plant material generally balance the photosynthetic capture of carbon, the process is neutral from a sustainability perspective, except where methane is emitted. This argument applies to the primary product as well, excepting that all production inputs and resulting emissions over and above the natural cycle are attributable to the product. Other treatments of the waste-stream, or end destinations of the primary product should be interpreted in this context. If the exergy of the waste-stream, or the final disposal of the primary product is leveraged to displace the consumption of fossil carbon, then a benefit results, potentially resulting in a net positive environmental outcome.

4.5.4.1 Energy content relative to supply stream inputs and losses

Returning to the central claim of this chapter, the inclusion of biomass exergy in embodied energy significantly reduces the meaningful value of the resulting indicator. The energy inputs measured at the point of end use on the demand-side may inadequately recognise the accumulated losses from supply through to end use. Cleland (2005) compared supply-side improvement options for domestic lighting from a coal-fired power source with demand-side options. He described the losses occurring through the supply system, and showed that only 0.3% of the original energy ended up as useful light. The ensuing analysis demonstrated that demand-side efficiencies (in this case the replacement of incandescent lights with compact fluorescent lights) were preferable to supply-side options (in this case replacement of the power generation with a combined cycle gas turbine). While the study focussed on electrical distribution, the principle can be argued to extend to other energy supply and distribution systems. The Cleland (2005) report can be argued to demonstrate that it is illogical to combine demand-side energy consumption with supply-side energy resources in a single indicator.

The energy balance of an energy supply stream can be represented as an inverted pyramid. In the case of hydro-electricity, the energy available is at its maximum at the beginning as stored lake water. Each transition through the production and delivery system results in the "loss" of some energy. In fossil fuel production the energy content of the substrate remains more or less constant, but the refining, storage and transport system requires energy inputs that must be accounted as an energy cost against the exergy of the substrate.

The supply stream for fossil fuels has been optimised through the 20th century as it has been a primary driver of global economics. Despite this optimisation, as global oil reserves became scarcer, the energy ratio for fossil fuels (the ratio of the energy available from a fuel to the energy expended through its supply stream) has been subject to downwards pressure. The calorific energy content of fossil fuels is conserved through the supply stream, but even so energy in fossil fuels can be represented as an inverted pyramid, as various energy inputs through the supply stream erode the energy ratio over time and distance. In the case of crop fuels, energy from sunlight is stored in the crop over a growing season, after which the energy costs parallel those of fossil fuels.

The energy available from food crops follows a similar pattern to that of energy crops, however this similarity is not sufficient justification for applying the same indicators to food and energy crops. In the case of an energy substrate it is logical to derive an indicator from the ratio of energy recoverable from the substrate, to the energy expended delivering it through a supply stream. However, for food, timber and other products for which the primary characteristics valued by the customer are attributes other than energy, the energy ratio indicator cannot be accorded the same meaning as when applied to fuel substrates.

4.5.4.2 An understanding of the energy in biomass

Biomass at a forestry production site is an energy source near the top of the inverted pyramid, whereas fossil fuels or electricity delivered to the same point are at the apex of their pyramids. This line of argument correctly values (as an economic *benefit*) a unit of energy within biomass at a production site many times higher than the same

energy unit contained in fossil fuel or electricity. Another way of saying this is that a unit of energy extracted from waste biomass at a production site could displace larger units of energy at a distant source of energy production. (This principle is reversed if we utilise biomass as a replacement energy source in the wider system.)

These arguments indicate that a unit of purchased energy as a production input is not equivalent to the same unit of energy contained as exergy in biomass. Both are useful and meaningful measures, but summing them generates ambiguities. We can however conclude that in principle it is preferable to utilise a biomass energy source close to the site of its production, early in the value stream rather than late.

This is simply observed in the use of biomass (whether or not we define that biomass as "waste") in the production of wood pulp or in milling. A unit of energy extracted near the source has few hidden inputs, whereas it is difficult to identify all the losses and wastes in a global (or even national) energy supply stream. A unit of energy extracted from forestry waste at or near a mill or pulp process site may replace an equal unit of fuel oil, but the actual efficiencies gained will invariably be greater than the metrics indicate, and never less. This conclusion has implications for the selection of strategies for the utilisation of waste biomass in apple production[41].

4.5.4.3 Summary of the treatment of exergy in biomass

The total production energy value, including the exergy, of biomass feedstock is a useful economic metric for producers of the product. This value represents the total amount of energy the producer needs to procure (whether by purchase as an economic cost, or freely from photosynthesis) to produce the product. The value that is reported as an environmental or sustainability indicator should however be reported separately from the exergy of waste biomass feedstock, notwithstanding that associated GHG emissions should be reported as an environmental cost.

This discussion demonstrates that the practice of including the exergy, or the total calorific content, of both primary products and waste products in the energy attributable to those products was relevant to the context in which the primary

---

[41] See App. V for an analysis of the energy available from apple prunings.

question was the total amount of energy required to produce a product. This was the context of a substantial volume of energy research initiated during the oil crisis of the late 1970s. In the current context where energy usage and carbon emissions are regarded as drivers of global climate change, a modified treatment of energy components is appropriate.

4.5.5 An examination of hydro-electricity

An argument can be proffered that New Zealand's hydro-electricity is a renewable and therefore sustainable source. Hydro-electricity is certainly renewable from the perspective of the hydrological cycle, but whether it is sustainable depends on value judgments made about the changes to landscape and ecosystems ensuing from hydro-electrical installations. It can be argued that it is reasonable to combine electricity and fossil fuel usage in a single indicator as a direct energy cost (Wells 2001), as although the environmental costs of these two sources are quite different, the energy content is more or less interchangeable on the demand-side. The orchard energy study (Sect.4.1) adopted this pattern. The combination of these sources in a single indicator draws from, and informs the dialogues ensuing from the 1970s energy crisis, but is less useful in informing a dialogue that includes the issue of bio-diversity. Whether the presuppositions embedded in these indicators adequately inform a discussion of global climate change requires further examination.

4.5.5.1 Bio-diversity as a common currency

The purpose of a sustainability indicator is to reduce environmental impacts to a common currency, so that different human activities can be quantitatively compared. Bio-diversity is identified here as a more meaningful "common currency" for assessing the impact of energy interventions such as hydro-electrical installations, in that habitat loss is an outcome of both global climate change and hydro-electrical installation.

The issues implied here are very messy, indicating the need for methodologies that can adequately describe complex inter-related issues (Frater and Houston, 2008). The bio-diversity loss implied in the ongoing use of fossil fuels has wide ranging implications for tropical rainforests, oceanic and polar environments (Melnick *et al.*,

2005). There are huge uncertainties and despite a level of consensus among climate change scientists (IPCC, 2007), a disquieting level of dissenting opinion exists. On the other hand, the environmental (and social impacts) of a new hydro-electric installation, although wide-reaching have a relatively high degree of certainty and predictability.

Bio-diversity may be a common currency, but it doesn't provide easy units for comparative debate. On the other hand, energy indicators appear to offer comparable units for debate, but the presuppositions embedded in energy indicators published within the last decade do not necessarily mesh with the scientific and political frame of reference of the current sustainability debate.

The arguments offered up to this point demonstrate the thesis of this chapter; the context in which research is conducted inevitably leads to hidden presuppositions and value judgments being embedded in numerical indicators. Those indicators may subsequently be regarded as objective and value-free, and adopted by future studies on the basis of precedence following the paradigmatic pattern of building scientific knowledge (Popper, 1972). This issue is critical to energy studies, where published data may be offered as a basis for international policy debate and the strategic management of food supply streams. The argument proceeds to a more general discussion of the dangers for scientists in drawing conclusions that impact on social, environmental or political systems.

4.5.6 An example of mixed energy inputs in reported indicators

A Swedish LCA report on milk tetra brik production (Rydberg *et al.*, 1995) reported the production of pulp utilising biomass sources resulting in a net energy surplus (see also Sect. 3.4.2). The study acknowledged that feedstock energy was included in the analysis, but the ramifications of this inclusion were not addressed in the report itself. This study clearly combined demand-side energy consumption with a supply-side energy source. The LCA methodology itself is not questioned, as the inputs to the production system were reported minutely, and could be re-analysed in subsequent studies with a revised frame of reference. However, reporting a "net energy surplus" for any aspect of production is a politically attractive finding that could find its way

into popular press, and even political policy. I have previously argued (Frater and Houston, 2008) that the:

> "application of scientific methodologies to complex systems has inherent limitations that should be explicitly acknowledged by the researcher, and reflected in the both the experimental design and the presentation of findings."

We continued:

> "the scientific method reduces and simplifies the complex system to metrics that invite the observer to form value judgments. The arena of energy usage and carbon emissions is globally topical, and the risk is that value judgments beyond the authority of the actual research may be formed from research findings by popular press or political interests. Although not a deliberate experimental intervention, the simple act of reporting data may engender a response that is unexpected and inappropriate."

Specifically addressing the LCA methodology, we stated:

> "A criticism of this style of analysis is that the functionality and practicality of the method can arguably take precedence over a holistic, systemic viewpoint. Advocates of the LCA method would no doubt dispute this criticism, as the rationale for the development of the LCA method was to provide a holistic understanding of production systems. However, now that the method exists, the danger is that it is followed prescriptively without recourse to broader systemic enquiry."

We concluded:

> "The use of hard systems methods alone may well provide metrics that appear to be useful, but the use of those metrics to drive organisational strategy and policy must be questioned. Locating hard systems methods, and reporting results derived from them, within an overarching soft systems approach should

provide a structure and mechanism for examining global supply streams in an

holistic and robust manner."

The argument proposed was that interests far beyond the scientific community could

adopt the conclusions of wide-ranging environmental studies. LCA studies for

example are frequently initiated by political agents. Therefore it is not sufficient

simply to report the results without commenting on the meaning of those results in the

broadest context. Those comments must be informed by the most appropriate

disciplines. The level of focus provided by methodologies such as LCA may work

against the participants in drawing conclusions from the study. Thus, when Rydberg

et al. (1995) reported a net energy surplus for a significant segment of an important

product, the location of this research within an overarching systems approach might

have prompted a more cautious conclusion.

Far from being an isolated case, it could be argued that the results of environmental

sustainability studies frequently report conclusions that would be viewed quite

differently if the hidden assumptions had been surfaced through systemic

examination. The conclusions drawn by the scientist are invariably those that are

reported and used in policy development. Selke (1999) reported another example of

what is argued here to be inappropriate logic (for application to current global issues).

The author cited a report (Gaines, 1981) offering values ranging from 58.8 MJ kg^{-1} for

natural linerboard to 77.6 MJ kg^{-1} for bleached board. She reported that the use of

recycled fibre yielded an "energy savings" of 46.4 MJ kg^{-1}. A value of 37.3 MJ kg^{-1}

for the production of "corrugating medium with a recycled content of 30%" was

reported. In this study, 75% of the energy was provided from wood or wood by-

products, with the remainder being "purchased energy". Significantly, this value

included the combustion energy of the raw material.

The indicators reported in these studies offer benchmark values for globally important

packaging products. The method by which these values were interpreted has resulted

in an accumulated set of assumptions being embedded in the more recent reported

indicators. The discussion of inputs and losses through energy supply streams, and

the discussion around mixing environmentally harmful, neutral or beneficial energy

sources, indicates that those reports exemplify findings that are not valid outside of their original context. However the authors were careful to explicitly acknowledge the method by which, and the context in which, the indicators were constructed. The issue is one of "caveat emptor" – it is up to the user of the indicators to demonstrate synergy (or asynergy) between the early context and the new context.

An aspect of these conclusions that is challenged is the interpretation of the reported values as an environmental cost. It is further questioned whether combining biomass energy components into a single metric is meaningful for contexts other than the specific context in which they were measured. A hidden assumption is that if energy inputs can be reduced to common energy values, then it is valid to sum them. This assumption fails to recognise that the values are points in a process, not static entities. That is, that the actual cost or benefit of a unit of energy varies according to the point in a value stream at which it is injected or extracted. It may well be appropriate to derive an average energy cost for the delivery of fossil fuels in a global market, and thus to settle on a single representative indicator. The same logic cannot be applied to biomass resources where they can be utilised before they enter a global or national value stream.

Focussing on numerical indicators has attendant risks. Indicators are simple metrics, allowing the least knowledgeable commentator to compare one system with another. Issues such as environmental degradation, loss of bio-diversity and wider human ramifications may be more significant, but the simple numbers may well be accorded greater attention than balanced commentary.

4.5.6.1 The practical application of benchmark data from forestry products

The actual inputs in any specific value stream can be modelled and subjected to improvement methodologies (Rao, 1997). An individual exporter has the opportunity to demonstrate that their value stream performs better than the benchmark energy value. Opportunities exist throughout the forestry products value stream (McClintic, 2008) to utilise energy derived from waste biomass, and some manufacturers of timber products already utilise these energy sources. Preceding arguments concluded

that any use of surplus biomass from within the feedstock value stream would be neutral with respect to sustainability criteria, and that those energy sources should not be included in the embodied energy of a product. The arguments provide a justification for excluding the biomass exergy component of apple packaging from the values reported herein.

4.5.7 Hidden assumptions in a methodology

The following discussion considers the gathering of information, and the exchange of knowledge within organised systems. The transfer of a methodology from an industrial context (quality methodology) to scientific research, is discussed. The specific industrial context is that of "lean thinking", as it evolved in the Japanese automotive industry[42]. The actual deployment of lean thinking in food supply systems was proposed and implemented by Simons and Mason (2003). This exploration of lean thinking provided a key example of tacit knowledge and value-rich assumptions being imbedded in methodology, potentially resulting in unforeseen systemic consequences.

4.5.7.1 The movement of information through organised systems

A general principle of the transfer of information within organised systems, such as global food supply chains, is that information is required to be attenuated when it passes upwards through organisational levels (Beer, 1979, Beer, 1981). Decision-makers cannot be expected to cope with all the variety observed at the production level. The reduction of information to forms that can be easily assimilated by high-level decision makers, while retaining and clarifying critical elements is a critical task for middle management. Scientists engage in a similar process, gathering information, deriving meaning from it, and passing the attenuated information (e.g. sustainability indicators) to decision-makers and researchers. It is not surprising therefore that methodologies from organisational management have been adopted in scientific enquiry.

---

[42] Some arguments presented here were published as research notes (Frater and Houston, 2008)

4.5.7.2 Integrating lean thinking and environmental sustainability

The demand for sustainable food production has led environmental practitioners to examine and deploy methods developed in manufacturing industry for improving systems and reducing waste. Lean thinking is one of the most influential new paradigms in manufacturing (Hines and Rich, 1997), resulting in the exploration of lean thinking by environmental practitioners, and adaptation of lean methods to address sustainability issues (Simons and Mason, 2003).

Lean is an evolving concept, moving from its origins in shop floor Japanese automotive manufacturing through to global supply chains (Hines *et al.*, 2004). Its recent deployment as a sustainability tool requires a reconciliation of lean and sustainability concepts. Without reconciliation, there is a danger that lean methods may be used in inappropriate ways, or that incompatibility in the presuppositions of the industrial and scientific paradigms may undermine its future usefulness. Lean thinking has proved a powerful methodology in industry, so its adaptation to the field of sustainability warrants investigation. The areas in which potential differences of understanding or even conflicts are apparent are the concepts of waste, value and customer focus.

4.5.7.3 Waste, value and customer focus

Lean thinking is built on customer focus. The concepts of waste (muda) and value are defined in terms of the end customer. This focus was introduced in the kaizen philosophy (Imai, 1986, Imai, 1997). Kaizen is process focussed, and defines supplier-customer relationships throughout the process chain. Lean thinking, while recognising the kaizen tools and hence the internal customer, focuses primarily on the end consumer. Neither of these two approaches is fully acceptable to the environmental practitioner, as the environment is regarded as having intrinsic value of its own, for which the customer is merely an advocate (Sect.2.6.1). Hines *et al.* (2004) stated that:

"the customer values a wider and more complex range of tangible and intangible attributes such as brand, image, environmental issues and local production."

However, if environmental concerns are limited to value attributes desired by the customer, then the food producer is free to operate in ways that it knows to be environmentally unsustainable so long as the customer doesn't care. An individual food producer may deal with a variety of global customers, each of whom will have a different perspective on environmental issues. In the farm and post-harvest studies (Sects. 4.1, 4.2) this awareness was reflected in stringent environmental quality demands for European markets. By comparison, the quality focus for North American markets was biosecurity. Political pressures and media influence may result in the end customer having a less balanced viewpoint than an independent observer.

An uneasy resolution is found by regarding the end customer as the advocate of best practice. The situation observed in the post-harvest case studies was that distributors (such as supermarket chains) were the arbiters of best practice, and while they might be influenced by popular beliefs, they were at least in a position to educate or influence customers' understanding. Even if the distributor were to adopt policies that recognise and value best practice understanding of sustainability, there was a significant danger that commercial constraints and political pressures would influence their decisions. A further difficulty for the producer was that achieving best practice for a market that didn't value it would incur disadvantageous costs.

Returning to the examination of lean thinking, the practice has advanced from being a process-based methodology to a strategic methodology (Hines *et al.*, 2004). At the strategic level lean thinking advocates and enables long term solutions that provide mutual benefit for both supplier and customer throughout the value stream. If lean thinking were to be extended to sustainability issues, then both the supplier and customer must act as advocates of global sustainability. In a competitive marketplace, advantage gained by one supply chain is achieved at the expense of another supply chain. The deployment of lean thinking to achieve sustainability goals certainly achieves advantage at the supply chain level, but whether this extends globally – to mankind - is questionable. It can be argued that advantage gained by one supply chain will be recognised by the customer, and the subsequent success of that supply chain should result in global improvement. However, the principle of global

sustainability must be engineered into the lean methods to avoid strategic decisions that have negative overall consequences.

Lean methods were not developed to address systemic improvement on the global scale, however they are capable of providing improvement on a scale beyond local process silos. The adoption of soft system methodologies proposed in Sect.4.3 would provide a measure of safety in methodological transfer across disparate disciplines.

4.5.7.4 Sustainability and the application of lean methods

Hines *et al.* (2004) described the evolution of lean thinking from prescriptive cell and line process improvement in the 1980s, through broader-based shop floor methods and onto value stream mapping in the 1990s, and beyond single loop learning to double loop organisational learning requiring systemic understanding. While lean thinking has progressed through this path, it is reasonable to expect that all of these phases will still be represented in the lean activities of organisations. Advanced lean thinking organisations deploy lean concepts at the strategic level, and prescriptive lean methods at the line and process level.

The lower level, prescriptive lean methods could be deployed as sustainability tools, without any grave fear of unexpected systemic consequences. That is, a focus on waste reduction at the process level is simply going to achieve greater efficiency including reduction in environmental costs. These methods should be able to be applied confidently, with the specific goal of reducing energy inputs and carbon emissions. Even the most far reaching of the early lean practices (those requiring co-operation and long term commitment between organisations in the supply stream) would appear to offer win-win solutions, improving cost effectiveness and environmental sustainability.

The most recent iterations of lean thinking (strategic level rather than process level) offer the greatest benefit to the organisation, but also the greatest risk of systemic error. Lean thinking at the strategic level offers considerable benefit to the organisation deploying it, but could also potentially generate harmful systemic effects from an environmental or sustainability perspective. If decisions at this level were

made to benefit the supplier and customer, albeit accommodating the most altruistic motives of the stakeholders, the actual systemic results could be quite different to those anticipated. The far-reaching nature of lean practice provides no demarcation line between safe practices and practices that might engender unforeseen systemic consequences. Environmental sustainability issues occur at local, regional and global levels, so the more significant the intervention, the more critical it is to deploy best practice in systemic analysis.

4.5.7.5 Reconciling the lean and environmental concepts of waste

Returning to the issue of lean waste and environmental waste, waste is defined within lean thinking as anything that does not provide value. Consequently, value is the more critical concept. Hines *et al.* (2004) attribute the "crystallisation" of value as the first principle of lean thinking to Womack and Jones (1996). The value chain (Porter, 1985) anticipates some value stream thinking, and kaizen literature (Imai, 1986, Imai, 1997) contains enough explicit and implicit reference to value to indicate that the concept was firmly established in Toyota's thinking if not a wider spectrum of Japanese industry prior to that "crystallisation".

Hines *et al.* (2004) discuss the cost-value proposition as defined by the customer. They describe how value can be increased by reducing wasteful activities and their associated costs, or by offering the customer additional features or services. To reconcile this thinking to an environmental understanding of value, we can first acknowledge that the customer will have an appreciation of environmental issues. Secondly, the "cost" can be equated with energy usage or carbon emissions as indicators of overall environmental degradation. However, we have already argued that the customer is an inadequate reference point for environmental issues, and that the customer must be regarded as an advocate of best environmental practice. It follows that in an environmental lean study, the concept of value must be broadened to incorporate all the benefits embodied in a product whether or not the customer recognises them, just as the cost will incorporate all the energy and emissions embodied in the product or process.

4.5.7.6 A resolution of differences in tacit knowledge

The broad understanding of both customer and value brings about a level of resolution of the difference between the environmental understanding of waste and the lean definition. In lean thinking waste is the antithesis of value, defined and characterised as Toyota's seven wastes (Womack and Jones, 1996). Environmental waste is typically expressed as emissions. Treating the customer as an advocate of environmental best practice offers some reconciliation of these concepts, as emissions result in a loss of customer-defined value (that is, loss of value as recognised by a hypothetical, environmentally responsible customer).

The exploration of the terms waste and value demonstrates how tacit knowledge is embedded deeply in methodology, affecting the language by which methods are described, and consequently the meaning, validity and transferability of results achieved through the methods.

4.5.7.7 Concluding arguments pertaining to tacit knowledge

Tacit aspects of the broad field of sustainability are argued to be imbedded in the energy indicators reported herein. For example, New Zealand's electrical production system, which is about 70% renewable[43] (Cleland, 2005, p3), can be argued to be a more sustainable energy source than fossil fuel inputs. Various normative judgments underlie that argument, exemplified by conflicting viewpoints on the historical and present development of major New Zealand hydro-schemes (Sect. 4.5.5).

Fertiliser usage, and specifically urea usage, is an area of the present study where the indicators failed to provide an holistic picture. Tacit knowledge framed within environmental and political viewpoints is imbedded in the use of nitrogenous fertilisers. Some of this tacit knowledge is normative in nature, and is not even considered at the boundary definition stage because it is not consciously accessible to the researcher. An example of the normative values imbedded in urea usage, is the ownership and depletion of the natural gas fields from which urea is manufactured. Ulrich (2002a) requires the competent researcher to question who speaks for future

---

[43] The renewable component comprises a mix of hydro, geothermal and wind generation.

generations, however the morality of depleting non-renewable resources is likely to be excluded from LCI boundaries.

Organic fertilisers provide another example. If compost were derived from recycled materials, or material that would otherwise contribute to waste streams, then it could be argued to constitute a 'free good', notwithstanding the feasibility of carbon sequestration. Correctly formulated organic fertilisers contribute to, and enhance a range of soil fertility parameters, including soil structure, aeration, moisture retention, cation-exchange capacity, pH and availability of plant nutrients (Luke, 1968b). Conversely, if the inorganic fertilisers contain energy components that are derived from fossil fuel or nuclear sources, then they incur the sustainability costs associated with those sources.

Organic apple production emerged as a market driven response to an awareness of both human health and sustainability issues (Condron *et al.*, 2000). Issues of energy use in OFP production could therefore be argued to exist within a frame that acknowledges that awareness. If metrics used to inform a study such as the present research are constructed from a different frame of reference, they may contain imbedded assumptions that are antagonistic to the ethos of organic production.

Any comparison of alternative food delivery systems requires normative judgments at a deep level. For example, what is the nature of alternative energy sources for various pathways? Who owns or benefits from the use (or depletion) of those energy sources, and who receives or should receive the emissions of such a system (Sects. 3.3, 4.3).

From an environmental sustainability perspective, indirect energy metrics are a contributing component to broader issues of emissions and environmental impact, and although the total life cycle emissions and impacts are the drivers for policy, the energy indicators are a useful predictor of those impacts. From the perspective of the philosophical and systemic issues (Sects. 4.3 – 4.5), indirect inputs contain both explicit and tacit assumptions that materially affect the meaning of the reported indicators (Sect. 4.5). The metrics reported for the energy consumed in the manufacture of agrichemicals and fertiliser have been subject to a progressive change

in meaning; meaning that has been framed in an evolving the global context (Sect. 4.5.3.1). The frame has changed from a context where the primary concern is fuel shortages to a context of concern about climate change.

The extraction and manufacture of substances and the sources of the energy used to achieve those processes have value-rich implications that are imbedded in metrics. The terms "sustainable" and "renewable" are argued to be highly value-rich, and where those terms are imbedded in sustainability indicators, the frames in (and from) which they were constructed should be actively surfaced.

The systemic implications of these issues require a much broader approach than the present energy usage assessment. A theme of the present study is the limitations of the life cycle assessment (LCA) approach with respect to the emergent properties of global food supply systems (Sect. 4.3). An LCA study of a food supply chain provides metrics (many in the form of sustainability indicators) that can be utilised to construct models to inform decision-making processes. However, the argument proffered is that even a theoretical, complete LCA, and models informed by it, would be inadequate on two grounds:

-        the LCA study would contain tacit assumptions at every level, the validity of some assumptions potentially compromised by rapid changes in the global environment, while others, of an ethical or normative nature, would not be adequately recognised at the boundary definition stages; and

-        the emergent properties of the system, particularly properties relating to regional, national and global social, economic and natural environments are invariably outside of the boundaries of the study.

Other researchers (Tukker, 2002; Finnveden *et al.*, 2009) have explored these themes, offering methodological improvements. I have argued herein for a need to recognise the guidance of systems thinkers in the further development of LCA.

4.5.8 Discussion – further methodological aspects

4.5.8.1 Retrospective comments

The top-down methodology provided a more complete understanding of the New Zealand apple industry than previously available. If viewed alongside the Milà i Canals (2003) process case studies, the combination of contrasting methods and scales provided a more holistic viewpoint than either method in isolation, following the approach recommended by Giampietro (2004).

 The sample group represented the main growing regions, and provided a useful comparison of IFP and OFP production protocols, conventional and intensive growing systems and a representative range of scale in terms of operation size. Of these, the intensive group provided the least authoritative information, as in most cases the intensive planting formed only part of a larger conventional operation, resulting in ambiguity in energy attribution.

Two approaches were used for measuring capital energy inputs. Machinery items were surveyed in a sub-set (n = 8) of the larger sample group. This approach was closer to the case study approach than the top-down approach. The second approach, adopted for items such as tracks, buildings, irrigation materials and horticultural structures, was the development of a model based on assumptions derived from my personal experience in Hawke's Bay orchards. The adoption of a case study approach could be argued to be more rigorous than the modelling approach however the difference between them was that the case study approach shifted uncertainty from the accuracy of measurement to the legitimacy of industry wide extrapolation. The assumptions of the model were explicitly stated and would be more readily challenged than case study, while the case studies were empirically accurate for the sites measured. The assumptions (both implicit and explicit) in the methodology used to derive energy content for capital items have the potential to alter the reported indicators significantly more than the measurement methodologies or site-specific variation.

The structure of some medium to large-scale organisations, where they had adopted a strategy of owning orchard and packing operations, but using centralised coolstore facilities, created an opportunity that was not recognised at the time of experimental planning. In retrospect, this structure indicated that their packing facilities were relatively discrete, which, if studies had been supported, would have helped eliminate some of the uncertainties around the allocation of energy between packing and refrigeration processes.

This study was envisaged as an energy study. If the study had been planned from its inception as a component of an LCI, the use of LCA allocation protocols specified in ISO 14044 would have reduced ambiguity and uncertainty, and made the findings more useful for subsequent research.

Recognition that the process approach adopted by Milà i Canals (2003) was appropriate for his case studies of apple orchards suggests that a bottom-up process-based LCA approach at a lower structural tier might have been achievable for the two post-harvest case studies. It is likely that a process approach would have resolved uncertainties that appeared in the distribution of energy usage between various post-harvest processes. However, it is questionable whether a process approach alone would have resulted in more reliable overall energy usage values. A hybrid approach using both methods almost certainly would, and post-harvest studies using process or modelling approaches are recommended as an avenue for further research, and as a future balance to the present study.

4.5.8.2 Post-harvest attribution issues

A question arose as to which part or parts of a crop should be used as the denominator of sustainability indicators. Werner (2005), reviewed in Sect.2.0, considered the issues of attribution and ambiguity at length. He warned of the impossibility of deriving unambiguous repeatable measurements from material flows through complex situations. The movement of perishable products, and the resulting determination of attribution denominators in the post-harvest refrigerated value chain exemplified this problem.

If energy or emissions were to be attributed to the entire harvested crop (the gross value), then the resulting indicator would be lower than if it were attributed to the net value, or the export component. The use of the gross value as the denominator can be considered a default position for agricultural energy accounting.

In the orchard energy study this position was arguably correct, as the energy inputs at the orchard level resulted in a gross crop at the farm gate. How that crop was differentiated into products of varying customer value should not have affected the attribution of energy costs or emissions to farm production.

Once various products are differentiated in post-harvest processes, the energy costs should be attributed to individual products, either singly or collectively. Thus shipping costs were assigned solely to product that was shipped. In fact the methodology in this study for assigning shipping costs was based on shipped volume, so it would be illogical to use the gross crop as the denominator from the departure port onwards.

However, the nature of onshore storage, combined with the mid-level data gathering process of the present study, produced an ambiguity between packing processes (product differentiation stage) and shipping. While export product may have been stored in segregated rooms to comply with bio-security requirements, the energy inputs were not differentiated. That is, refrigeration plant and its energy inputs were shared between rooms that were physically separated, but adjacent. Consequently the energy costs of incoming products from orchards were not able to be differentiated from stored local market product or packaged fruit destined for export. This ambiguity also applied to the related indirect energy component.

Where various products are stored in the same room (a situation similar to multiple rooms under a single meter), the most appropriate method for allocation of emissions is reported to be heat load analysis alongside a consideration of refrigeration system efficiency (East *et al.*, 2009). This guidance should certainly be followed in future studies of this nature.

In this study, the gross crop became the default denominator for all onshore energy measurements other than fruit waxing and land transport, which could be correctly attributed to the export crop. From the export port onward, the actual volume transported was the denominator for energy indicators.

This discussion impinged on the issues of normative values, assumptions and tacit knowledge imbedded in sustainability indicators investigated in Sect. 4.3. Even if a methodology were devised to accurately attribute energy to the crop components that were identified as generating ambiguity, normative issues (Frater and Houston, 2008; Johnson, 1984; FAO, 2006) might remain unanswered. An alternative approach is proposed in Sect. 4.4, where it is concluded that a feasible solution to resolving ambiguities is to combine positivistic and normativistic knowledge in a dynamic system modelling approach as part of an holistic intervention methodology.

4.6 Retrospective TLCI

If the TLCI approach had been applied to the present study, at least some significant differences would be evident, both in boundary definition and in conclusions and interpretation of the study. Although the apple energy study was designed as an energy study, data measured and results reported arguably could be adopted as components of a life cycle inventory (LCI). In the TLCI approach (Fig. 27), LCI (stage 1. of TLCI) is informed by stage 5 (system management). TLCI as a whole is a dynamic model, so that LCI data would be reviewed in the context of stage 5, which is framed in terms of purposeful change. Stage 5 is informed by normativistic information (stage 2) and a dynamic system model (stage 3).

At the early stages of LCI data gathering, the TLCI model would have required the parallel deployment of soft systems tools to surface assumptions and query boundaries. This differs from the model proposed by Bras-Klapwijk (1998) where a further stage is added to the LCA process, in which "values and frames" are investigated by "scientists and others". It also differs in that stage 2 of TLCI occurs alongside LCI, not subsequent to it, and that the soft data is further amplified (Beer, 1984) by examination through a systemic intervention frame (Midgley, 2000).

If this process had been followed in my study, more attention would have been given to the assumptions imbedded in boundary decisions (e.g. the recognition of physical boundaries but not social boundaries). The critical systems heuristics approach (adopted as a 'method' in stage 2 of TLCI) further requires that the researcher queries who *ought to be* the client or beneficiary, what *ought to be* the purpose of the research and who *should be* regarded as an expert. These questions might pose significant difficulties when the research has been sponsored by an industry body, however the adoption of this process would lessen any potential risk of perceived bias.

The methods specified in my TLCI model for surfacing assumptions, and examining boundary decisions are the SAST method and the CSH approach. The SAST method (App. XII, p279) would have been undertaken by group of selected stakeholders. Those stakeholders would have liased with, and probably been involved with the LCI data gathering process (which in this study was achieved by surveys and personal interviews). The CSH approach is much broader, but could have been initiated by the same group of stakeholders. The CSH approach cannot be defined as a bounded method. It could have been expected to inform the subsequent direction of the study, such as indicating the deployment of alternative methods.

The development of a dynamic model would have allowed possible future states of the food supply system to be explored. In the apple study, a suitable dynamic model would have consisted of a software SD model that would have been developed using both hard and soft data. This stage might allow the researcher to explore the consequences of adopting the various frames identified by (Tukker, 2000). Recognition that the process constituted an intervention would inform the researcher of possible real world consequences, and possibly guide the researcher to the adoption of a precautionary frame, particularly with respect to potential causal loops in the dynamic model.

An example follows of the complex interactions that were largely ignored in the present study, but which might have been meaningfully engaged in the TLCI approach. An argument can be made that the environmental well being of a country is closely linked to its political and economic security. The present global issue of

rainforest destruction demonstrates the difficulty in controlling detrimental practices where populations lack other sustainable sources of economic wealth. Similarly, where states are subject to warfare, harmful environmental practices go unchecked (e.g. the use of defoliants with persistent environmental contaminants during the Vietnam conflict). If this link were accepted as valid, then the support of the economy of any state would be regarded as a positive systemic influence, and damage to an economy would be regarded as a systemic threat to the local environment. Thus, in a TLCI approach, the systemic model would inform boundary definitions so as to include critical or unique ecosystems in the production environment, including the influence of the local or regional economy. This type of model could include the economies and ecosystems of regional labour suppliers (such as Pacific island nations). The systems dynamics component would potentially provide a range of possible system states, and the relative influence of different interacting components could be modelled over a projected timeframe.

The deployment of the CSH tool would allow the modeller to take some account of whether those modelled states were good or bad for stakeholders, or local or regional ecosystems (irrespective of the value placed on them by human stakeholders). Thus a positive economic outcome for a Pacific state might support local communities, reducing deforestation pressure, potentially influencing the regional energy flux on a significant scale.

The area of packaging was recognised as a significant input, and one that was highly sensitive to presuppositions. This area would have benefited from an examination of normative presuppositions, and from modelling of future stages with respect to the treatment of recycled materials and waste forestry products.

A final example is offered: a systems model might radically change the understanding of the potential influence of the use of composted materials as an alternative to mineral fertilisers in IFP production systems. While the LCA component would proceed in the normal fashion, its placement in an holistic intervention model would allow the practitioner to move towards reconciliation of the disparate worldviews of 'organic' and 'conventional' production (Rigby and Bown, 2007).

The TLCI approach is claimed to address the issues identified and explored by Tukker (2000, 2002), Finnveden (1997) and Finnveden *et al.* (2009) in a manner that is more fully informed by the body of knowledge supporting systems thinking than previous approaches.

Chapter Five - System Summary, Further Work and Conclusions

5.1 Combined system summary

Direct shipping was responsible for the largest measured system energy input, followed by the indirect shipping component (Table 29). The values reported for shipping were consistent with previously reported material, however the range of values (as derived from vessel specifications) added to existing understanding of the potential for the New Zealand industry to reduce its total energy consumption and emissions.

It is noteworthy that aside from shipping and packaging, the total farm contribution was significantly greater than the remaining post-harvest processes. This understanding confirms the adoption and development of IFP protocols as an appropriate strategy for reducing total system energy use and emissions.

The energy attributable to apples from packaging was found to be highly sensitive to assumptions, particularly with respect to the allocation of calorific energy content and carbon in wood-based products. Nevertheless packaging energy was found to be of a significant magnitude (Tables 29,30) relative to most other farm and post harvest processes.

The present study provided top-down direct energy usage data that measured the variation between orchards and districts plus production and growing systems. The reported values can be interpreted as industry benchmarks with a greater level of confidence than those provided by previous case study approaches. The variation reported provided the basis for future strategies for farm level energy and emission reduction, particularly if combined with previously reported analyses of variation within farm processes (Mila` i Canals, 2003).

The direct energy usage reported within post-harvest processes requires further clarification, as the difference between the two case studies was not fully explained. Nevertheless, the two values derived from observations provided an indication of

upper and lower limits for these parameters, and the mean value reported (Table 29) has provided an interim benchmark.

Table 29: Summary of combined system inputs

	System energy component	Energy (MJ kg^{-1})	Subtotal (MJ kg^{-1})
Transport	Shipping direct	2.66	4.29
	Shipping indirect	1.58	
	NZ land transport	0.047	
Packaging		1.46	1.46
Farm	Farm fuel	0.46	1.45
	Farm agrichemicals	0.31	
	Farm capital (plant and buildings)	0.30	
	Farm fertiliser	0.26	
	Farm electricity	0.12	
Post-harvest processes	Direct cooling electricity	0.32	0.51
	Direct packing / administration (electricity)	0.06	
	Direct lift trucks	0.045	
	Indirect coolstore buildings and plant	0.045	
	Direct waxing	0.021	
	Indirect packhouse plant	0.0085	
	Indirect refrigeration plant	0.0059	
	Indirect lift trucks	0.0057	
	Indirect other buildings	0.0003	
Total (MJ kg^{-1})		7.7	

The energy embodied in farm agrichemicals was found to be subject to high levels of uncertainty due to the lack of process information available from manufacturers (Geisler *et al.*, 2004). The methodological development used to measure these inputs (Sect. 3.2) provided a basis for an improved understanding of this area of knowledge.

Farm capital equipment was found to be of a surprisingly high magnitude. However, the reported values were subject to the assumptions of plant life prescribed by Pimentel (1980), and these assumptions require further clarification in the New Zealand context (Mila` i Canals, 2006).

Farm fertiliser was found to be directly, and systemically, linked to non-sustainable energy sources. Although the energy embodied in organic (typically compost) fertilisers was found to be comparable to that of mineral fertilisers, the comparative sustainability of the two nutrient sources requires further clarification. The empirical value of fertiliser inputs placed it below the level of those inputs requiring the most immediate attention (Sect. 5.2), however the link to fossil fuels demands a level of urgency in identifying alternative sources of soil mineral replenishment.

Of the remaining inputs, land transport was noteworthy because of its low magnitude. This value (0.047 MJ kg^{-1}), reflected the geography of New Zealand's apple growing districts and their proximity to ports, and to some extent counteracted the high shipping energy costs. The location of ports (Napier and Nelson) immediately adjacent to the two major growing districts is a fortunate attribute of New Zealand's production system.

5.1.1 Summary of the Original Contribution of the Energy Study

The apple energy study provided new knowledge in some specific areas of both New Zealand and global apple production:

-    previous apple energy studies had not considered the energy contribution of capital items to the extent of this study,

-    the present study provided more confidence in overall New Zealand industry inputs (at the expense of less process detail) than previous farm level studies, including values reported for farm-level and post-harvest contributions,

-    the variation of energy inputs between New Zealand regions, and between orchards of varying sizes had not previously been reported,

-    the finding that the energy usage of both OFP and intensive orchards in the sample group lay within the overall distribution (for every parameter other than indirect energy intensity per area) was a significant result,

-   the energy requirements of fruit waxing had not previously been reported, and the energy content of apple packaging material was poorly reported,

-   the energy use associated with urea (in NZ apple production) has not previously been reported,

-   the energy content of pruned apple wood had not previously been reported,

-   the methodology utilised for measuring the energy content of agrichemicals was a development of methods proposed elsewhere, whereas existing studies have invariably used more primitive methods, and

-   the energy contribution of refrigerated shipping of apples had not previously been reported.

5.2 Further work

5.2.1 Further work in apple production energy research

Enhancing the sustainability of New Zealand apple production was a core driver of this study. Therefore further work is addressed in terms of the potential benefit to that industry. The Pareto principle was applied to the empirical results of the farm level and post-harvest studies, in order to identify the areas in which future work should be targeted to further sustainability objectives.

The Pareto chart (Fig. 28) of the top 14 system inputs identified shipping and packaging as the "vital few" inputs. A 25% reduction in these three inputs would be equivalent to the total of the remainder – the "trivial many". Following these three, farm fuel, post-harvest refrigeration, farm agrichemicals, farm capital and farm fertiliser were next in significance, and of approximately equal order.

Notwithstanding the identification of shipping to the port of importation as the largest energy component of the NZ apple production system, previous work has demonstrated that domestic transport between supermarket and residence (Rizet, 2008), and commercial transport leading to the point of sale, may incur greater energy costs than production and delivery. These issues should be addressed first in an energy reduction strategy. Existing initiatives such as the delivery of bulk apples to
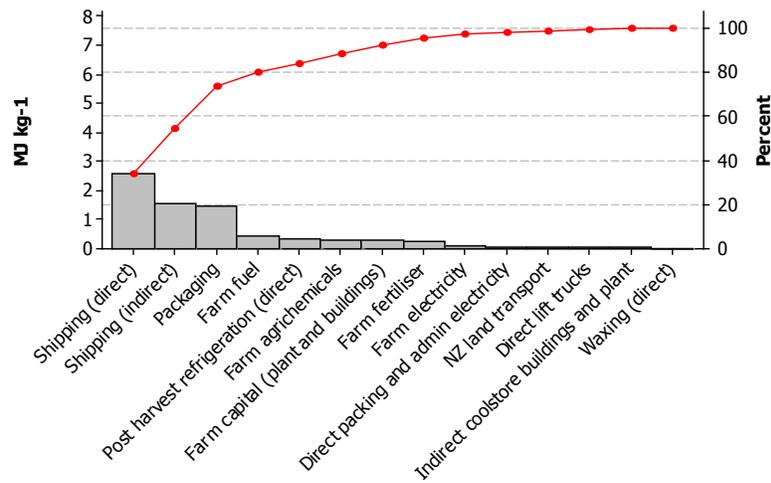
Figure 28: Pareto chart of the 14 highest system energy inputs

schools (de Sa, 2007), and supermarket home deliveries, do effectively address this issue, and could be examined further for parallel opportunities that bypass the domestic transport mode.

Rao *et al*. (1996, p167) reported two approaches for achieving improvement in a process variable:

- An innovation, or breakthrough approach
- A continuous, or incremental improvement approach

The quality science approach is typically deployed at a lower tier, at the factory or plant level, however the principle is argued to be equally appropriate at the scale of a global food supply chain. A variety of technological initiatives directed toward reducing shipping energy have been described, or are currently being explored (Sect. 2.3.2). While the New Zealand apple industry should not discount the possibility of developing technological breakthroughs in shipping, New Zealand does not have research resources for advancing shipping technology, and it would arguably be better to adopt a strategy of active participation in, and monitoring of, worldwide research initiatives seeking breakthrough change.

However, a continuous or incremental improvement approach would allow the New Zealand industry to address energy inputs in shipping from a "reduction in variation" approach (Rao *et al.*, 1996, Ch. 7). The variation observed in this report related to the superior performance of modern vessels, particularly noting the reduced energy intensity achieved by larger, faster vessels. Energy intensity values varied from +19% to –37% of the mean (Sect. 4.2.6.). It is not claimed that the scale of this variation is a realistic indication of the potential for improvement. However the existence of variation based purely on vessel performance has been demonstrated, and although it requires further clarification it has provided a potential mechanism for reducing the largest unequivocal energy input into the system. A strategy of identifying the most efficient vessels and subsequently securing their availability for transporting New Zealand's apple crop has significant potential for reducing the energy intensity of exported apples. Such a strategy might require capital investment on a regional scale for ports to comply with the requirements of large vessels, however such investment should be assessed in terms of reducing the major energy and emission component of the New Zealand apple production industry.

Factors surrounding routes, return loads and attribution for mixed loads also impact on energy consumption, and although they were outside the scope of this investigation they also warrant further examination. The relative energy requirements of the transport and refrigeration components of shipped apples require further clarification, particularly whether they are sensitive to vessel selection and route.

A strategy to reduce packing energy inputs would require a whole system intervention approach (as proposed in Sect. 4.4). This approach would constitute an LCA study to be conducted in parallel with an investigation of normativistic assumptions and boundary judgments (Sect. 2.7.1). Note that judgments of a normativistic nature are argued (in Sect. 3.4) to potentially alter the allocation of carbon inputs from a negative cost to a sustainable neutral position, or even positive sequestration.

Farm fuel costs were the largest of the system inputs that fell outside the "vital few" of the Pareto analysis. Nevertheless, they are an input over which the New Zealand apple industry has control, so they warrant attention. It has already been noted (Sect. 4.1) that the IFP protocols have addressed farm energy inputs at several levels, and

are a highly effective strategy for reducing those inputs, including direct energy inputs. The conclusion of Mila` i Canals *et al*. (2006) that energy consumption should be considered when designing certification schemes identified a potential mechanism for further reducing energy consumption. The extent of variation between sites was noted in Sect. 2.1, and while site and season specificity were acknowledged, the variation attributable to normal farm management practices[44] accounted for sufficient variation to warrant further analysis. The quality improvement approach recommended by Rao *et al*. (1996), of a combination of innovation and (variation reducing) improvement methods would be appropriate as an overriding strategy.

Post harvest refrigeration is the subject of a body of existing and ongoing research (Sect. 2.3.3). An area that requires further clarification is a systemic comparison of the storage of fruit under refrigeration with different energy systems, such as the mixed hydro, geothermal, wind and fossil fuel system of New Zealand compared to coal or nuclear power elsewhere. It is not presently clear for example, whether it is better to store fruit (before transport) in New Zealand, or to store it in destination countries. The boundaries of such an investigation should extend beyond those of a typical LCA study, taking into account the normativistic issues explored in Sect. 4.3, and could be achieved through the process proposed in Sect. 4.4.

Agrichemicals were found to be a mid-range energy component of the apple production system. The method for measuring embodied energy in agrichemicals was found to be poorly developed. An advancement to previous approaches was proposed and employed in primitive form, using the chemical structure of the active ingredient to predict the likely process precursor, and thereby derive the energy involved in the production of the product. Notwithstanding the argument that the publication of such data should be the responsibility of chemical production companies, further development of this method, or alternative approaches is required to provide a greater level of confidence in agricultural LCA studies.

Farm fertiliser was recognised as a component of the New Zealand apple production industry that is sensitive to changes in global energy costs. This area is of critical

---

[44] In quality science parlance, this is "common cause" variation.

importance to sustainable apple production, and further work is urgently required. The use of locally produced organic (compost) fertiliser as part of the IFP practices rather than just OFP should be investigated further (Elliot and Mumford, 2002). Alternative sources of nutrients from marine sources (e.g. shell from aquaculture) (Moon *et al.*, 1998, Huntley *et al.*, 1997) and from aggrading river system alluvium should also be assessed (Huntley *et al.*, 1997).

5.2.2 Further work in the systemic and philosophical component

A consistent finding of the philosophical and systemic component of this study was that ethical issues and value-rich boundary decisions impinge strongly on the understanding of global food supply systems. Soft systems theory and practice was identified as a mechanism for integrating these influences into scientific studies. However, soft systems thinking has emerged from the social sciences, and its application to areas such as food supply systems requires further investigation. The philosophical and practical approaches of Ulrich (1993, 2002a) and Midgley (2000) have provided a basis for structuring interventions into systems of critical global significance, and constitute a positive direction for further research.

The current (c 2009-2010) global pre-occupation with climate change, its implications for disadvantaged societies and the threat it poses to the sustainability of human populations demands a rich understanding of mechanisms for intervention. These areas are of pressing concern, and while the present research has proposed one mechanism for integrating the philosophical and systemic body of knowledge into the practice of environmental sustainability, further exploration of this inter-disciplinary field would reveal new understanding and result in new practices.

5.2.3 Further work in the proposed advances to LCA practice

The proposed development to LCA methodology (Sect. 4.4) requires LCA practitioners to assume a level of responsibility not just for scientific understanding, but for interventions resulting from that understanding. This approach would be structured within an interdisciplinary team research programme, including social and political scientists as well as environmental scientists.

The proposed methodology has been presented as a conceptual approach, rather than a descriptive methodology or prescriptive methods. The detailed application of the approach would be case specific, so further research would consist of applying the approach to a specific subject of concern. Existing LCA studies could possibly be integrated into the proposed intervention approach, however this retrospective integration would lose the advantage of cross-disciplinary learning.

A recommended progression of the proposed methodology would be to conduct parallel investigations into the positivistic science and the normativistic social science surrounding the subject of concern. The research would be managed as a single interdisciplinary team. The outcomes of the parallel lines of inquiry would be an LCA report for positivistic knowledge, and an equivalent un-prescribed condensation of normativistic knowledge. A subsequent, critical stage would be to integrate the two areas of understanding into a dynamic model, allowing an exploration of boundary decisions and interventions informed by the most complete knowledge available to the researchers. Systemic intervention should not be viewed as a subsequent stage, although deliberate interventions may be proposed and recommended to political agents. Systemic intervention is the undergirding philosophy bounding the entire process (Sect. 2.7.1.3).

An outcome of integrating LCA practice with a genuinely systemic approach, giving adequate consideration to both hard and soft systemic influences, should be that the outputs of the process would provide fairer comparisons of competing systems. A further outcome would be that LCA practitioners would take a higher level of responsibility for political or social intervention through the predictive modelling of future system states. These outcomes are argued to provide a greater level of safety, for both food producers and consumers, than existing practice.

5.3 Conclusions from philosophical and systemic enquiry

Global food supply systems are unique in the extent to which they interact with human and non-human aspects of sustainability. Findings from the study of these systems are deployed by social and political agents to inform interventions that might improve sustainability criteria. However this study has shown that the activities of

LCA practitioners constitute a form of intervention. LCA practitioners cannot consider themselves to be separate from deliberate intervention.

Boundary judgments are constructed by LCA practitioners in the context of a background of both explicit and tacit knowledge, aspects of which are deeply embedded in LCA methodology. Sustainability indicators reported from previous studies embody normativistic knowledge in the form of value-rich boundary judgments that may not be valid in new contexts. Positivistic knowledge is typically accessible at least in part to the practitioner, but normativistic knowledge is less accessible. Soft systems approaches provide a means to surface tacit normativistic knowledge and the adoption of system dynamics methods would provide a methodological link between positivistic and normativistic knowledge.

LCA can to continue to claim to be a methodology with holistic and systemic aims. This developing science must continue to take full account of the body of knowledge that informs systems thinking, including the emerging discipline of "systemic intervention". LCA practitioners should take a high level of ownership of intervention, and LCA practice should be imbedded in an holistic and systemic intervention approach.

Appendix I: Assumptions in the farm level study

Contents

I.I   Fertiliser energy assumptions and notes

Transportation, packaging and application (PTA)

Mudahar and Hignett (1987) reported that energy for transportation was directly proportional to the gross weight of the product, and was the largest component of PTA energy inputs. They offer a figure of 7.3 GJ mt^{-1} as a total PTA energy input figure, and this figure has been used for all fertiliser inputs. There are uncertainties implied in this figure, as fertilisers manufactured locally (such as lime products) would be overestimated, and fertilisers that are carried overland for greater distance may be underestimated. Similarly, fertilisers handled in bulk do not incur the same packaging input as bagged or palletised fertilisers. These uncertainties were not considered further here, but are of relevance to strategies for energy reduction.

Fertiliser energy values (MJ kg^{-1}) (Mudahar and Hignett, 1987, McLaughlin *et al.*, 1999)

	Production	PTA	Total
Urea	76.26	7.3	83.56
Ammonium Nitrate	66.59	7.3	73.89
Urea-Ammonium Nitrate	65.27	7.3	72.57
Ammonium Sulphate	58.05	7.3	65.35
Phosphate Rock (granulated)	7.10	7.3	14.4
Mined Sulphur	7.9	7.3	15.2
Potassium Sulphate	5.97	7.3	13.27

Single Super phosphate (1983)

Non granular	5.05	7.3	12.35
Granular	8.55	7.3	15.85
Triple granular (TSP)	2.5 – 8.87 (process dependent)		
Mean	5.6	7.3	12.9
Limestone	1.58	7.3	8.88
Dolomite	1.02	7.3	8.32
CaO	1.05	7.3	8.35
Kieserite	3.92	7.3	11.22
Nitrophoska Blue	40	7.3	47.3
Potash Gold	40	7.3	47.3
Organic	2	7.3	9.3

- Calcium ammonium nitrate (CAN) was treated as a mixture containing about 80% ammonium nitrate, and 20% calcium carbonate or dolomite. The energy estimate is 60 GJ mt^{-1}.

- Potash Gold super is a mixture based on potassium sulphate, with various nitrogenous compounds added. An intermediate value of 40 GJ mt^{-1} was assigned.

- Nitrophoska Blue is potassium sulphate blend containing nitrogen and minor elements. It was also assigned the intermediate value of 40 GJ mt^{-1}

- Magnesium Oxide was treated as kieserite.

- Unspecified fertiliser is treated as a mean value of 27 MJ kg^{-1}.

The energy values of organic fertilisers vary considerably depending on both the source and type of material, and other factors such as the means of collecting and transporting the material. A pure energy value could be misleading as it is presented purely as a cost, whereas there may be additional benefits (or costs) that are more significant from a broader perspective. For example crop yields were consistently higher when a combination of organic and inorganic fertilisers was used than when either one was applied alone (Parr and Colacicco, 1987).

The average energy values for beef manure, crop residues, sewage sludge and municipal refuse is 2.1 GJ mt^{-1} (Parr and Colacicco, 1987). Although it might be

reasonable to assume a lower packaging and transport value, in the present study the same PTA value (7.3 GJ mt^{-1}) was assigned as for inorganic fertilisers.

The energy value for organic fertilisers was calculated using the following density approximations based on the British standard BSI PAS 100:2005:

-Compost bulk density is assumed to be 400 kg per cubic metre.

-Moisture content is assumed to be 40%.

-Calculations are therefore based on a dry weight of 240 kg per cubic metre.

I.II   Fuel Assumptions

Fuel price(http://www.med.govt.nz/ers/oil_pet/prices/prices.html)

Diesel 54.24 (excluding taxes)

Petrol 53.18 (excluding taxes)

(53.18 x 1.47 = 78.2)

• Tax 47.4 per cent

(http://www.bp.co.nz/bin/press/item.pl?id=1123199177&showarchive=)

• Shipping product to New Zealand 3.6 per cent

• Crude oil, refined fuels, refining costs 45.7 per cent

• Operating costs, wholesale and operating margin 3.3 per cent

Energy in fuel (allowing for fugitive uses such as extraction, processing, refining)

Following Wells (2003)

Diesel   46.7 MJ l^{-1}

Petrol   42.3 MJ l^{-1}

Natural gas   50.3 MJ kg^{-1}

Lubricants   49.2 MJ l^{-1}

Conversions

One megajoule equals .2777778 kWh

One kWh equals 3.6 MJ

I.III   Production assumptions

One TCE is equivalent to 18.5 kg

Assume packout of 65% (based on anecdotally reported values from packhouse managers for 2003-2004 season)

Assume 400 kg per bin

I.IV   Capital inputs – methodological notes

Pimentel (1980) provided a methodology for calculating capital inputs for farm equipment. His methodology is based on the embodied energy in the raw materials, plus the fabrication energy, plus the energy required to repair and maintain the equipment over its useful life. His methodology requires that each item of equipment is placed in one of the classes he described, and that an estimate is made of the useful working life and the mass of the item.

The figures calculated in this study were based on the mass of items reported by the survey respondents. In many cases the mass was able to be derived from commercial sources (such as the agents for wind machines) and in other cases (such as deep well pumps and bore liners) by creating CAD models of the equipment and deriving the mass from those models.

In this study, orchard equipment has been placed in the following classes:

Class Two

- Tractors

- Windmachines

- Pumps (including risers and well casings)

Class Three

- Trucks, cars and utes

- Hydraladders

- Quad bikes

Class Four

- Sprayers

Class Seven

Mowers and implements

Tractor Notes

The estimation of tractor mass requires several assumptions. Modern orchard tractors do not exhibit the same relativity between power and mass as agricultural field tractors. Wells (2001) reports a more or less linear relationship between tractor power and mass over the full spectrum of tractor sizes, however this pattern is not reflected in orchard tractors. This is a result of the overall size of orchard tractors being constrained by their working space (inter-row dimensions). When orchard tractors are required to be more powerful to drive specific machinery (such as air-blast sprayers or mulching mowers), the tractor manufacturers have responded by increasing the horsepower of tractors without substantially increasing the overall mass. However the economic performance of apple orchards also impacts on these assumptions, as many orchards are not able to upgrade their tractors as frequently as they might wish to.

Milà i Canals (2003) reflected the presence of older tractors in the orcharding system by allowing a mass of 3400 kg for a 67 hp tractor, based on a single tractor from an orchard in his study, and a mass of 2300 kg for a 55 hp tractor. This study preferred a single mass of 2500 kg for all tractors. This is based on the assumption that lower horsepower tractors are frequently agricultural field tractors adapted for orchard use. These are relatively heavy, whereas high horsepower tractors are turbo-boosted versions of mid-size horticultural tractors.

Bore and Pump Notes

Average depths of wells on the Heretaunga Plains (Dravid and Brown, 1997):

29m (mean depth continuous well water level data)

35m   (mean depth manual water level network)

57m   (mean depth Heretaunga plains chemistry data excluding test bores)

Three sets of data offered for various purposes list well depths which vary from less than 10m to more than 200m. The mean of these three data sets (40m) is taken as a representative bore depth. It is recognised that aquifers in other parts of the country will differ significantly from this figure, but this assumption provides a reference point.

For a 300 mm bore of: 40 m depth with a 9 mm casing, the total mass of steel is 2743 kg, allowing for a density of 7.85 g cm^{-3}

Riser

    - assume:

        -150mm diameter

        -25m depth

        -8mm casing

Total mass of steel   779 kg

Deep well pump

Estimated mass 150 kg (Estimated on the basis of a solid "bar" of steel of the same diameter as the riser, 1m in length, or about half the length of a pump). Casing thickness varies from about 9 mm for large casings down to about 7 mm for small casings. A mass allowance of 150 kg is also allowed for surface pumps, except in the case of the 48 hp diesel pump for which 500 kg is allowed.

Appendix II: Pesticide energy notes

The most recent and comprehensive list of energy values for agrichemicals is offered by Green (1987). Other horticultural energy researchers have base their data largely on this work. Barbour (2004) assumed values respectively for herbicides, insectides and fungicides. Mila i Canals (2003) took a more sophisticated approach, following Green (1987) where possible, deriving other values using a methodology that calculated the energy value from the substance's reaction intermediate or precursor substances. The difficulty with this approach is that complex chemicals can be derived through multiple pathways, and the actual intermediates used by manufacturers are not known.

In my report, values reported by Green (1987) are transferred to other substances for which energy values have not been reported, where it is possible to show a reasonable similarity in biochemical structure or proximity in structural classification (as opposed to classifications based on mode of activity). This approach also allows us to adopt values from the full range of substances for which energy values have been reported, rather than limiting ourselves to (for example) the four fungicides listed by Green (1987).

Where there is no direct link in biochemical structure, a default value is required. There is no real justification for using the overall mean of 168 GJ mt^{-1} from Green (1987) for each of the three categories, as this implies a relationship between the mode of use of the chemical and the production energy that simply doesn't exist. This is borne out by the appearance of substances of similar structure in two or more categories.   The use of any sort of statistically derived value is equally difficult to justify, as statistical methodologies require that the raw data exhibit randomness, or some approximation to a normal distribution. Thus is certainly not the case with this data set.

A more conservative value (251 GJ mt^{-1}) derived from Green (1987) is used here as a default value. Other values are derived from this as well based on the relative complexity of the chemical structures from a manufacturing perspective. The

following notes describe a number of chemicals for which no definitive energy data could be found. Arguments are provided for the values adopted in this study.

Fluroxypyr was attributed the same energy as dicamba, due to its similarity in structure and proximity in classification.

The conazole and triazole fungicides are attributed the same energy as benomyl.

Organotin compounds were more problematic, in that none of the data from Green (1987) was directly analogous to the organotin compounds. These compounds are derived from stannic chloride, and while appearing to be large complex molecules, have some advantages from a manufacturing perspective in that they contain repeating ring structures. These structural patterns suggest that the compounds should require relatively few process steps compared to other acaricides such as cypermethrin, which has as similar molecular weight, but less symmetry in its structure. However, there is no obvious justification for assigning a low energy value. The mean of insecticide values (214 GJ mt^{-1}) or the median (157 GJ mt^{-1}) are possible default values. However, a conservative value, that of the acaricide fenpyroximate (251 GJ mt^{-1}) was adopted here.

Dodine (also known as cyprex or cytrex) is an important chemical which isn't represented in published figures. Mila i Canals (2003) treated dodine as the herbicide metolachlor (276 GJ mt^{-1}), however the justification for this is not obvious. In my report, dodine was treated as benomyl (397 GJ mt^{-1}) a molecule of similar complexity although quite different structure.

The fungicide dithianon, a quinine based fungicide was treated by Milà i Canals (2003) as "average fungicide". The average from Green (1987) is 168 GJ mt^{-1}, which is a similar value to that attributed to the insecticide carbaryl (a two ring compound derived from napthalene). Dithianon is classified as a quinone derived chemical, and quinone is itself derived from napthalene or benzene. Although this implies an extra manufacturing stage, the compounds are similar enough to justify using the average figure. A similar argument can be used for pyrimidine fungicides (e.g. cyprodinil and fenarimol), although some pyrimidine based compounds such as bupirimate appear

more complex and may well require separate calculation. The auxin naphthaleneacetic acid (ANA) should be derived from napthalene, so the same value was used.

The strobilurin fungicides appear more structurally complex than the napthalene derived fungicides, but they belong to a class of fungicides derived from naturally occurring substances, and although the actual pathways for manufacturing them are not publicised, it is possible that relatively energy efficient microbiological processes are utilised. The average figure is used following Mila i Canals (2003) but it is quite possible that a lower figure could be justified.

The sulphamide fungicides (e.g. tolyfluanid) are a relatively large complex molecule based on a single benzene ring. In this study, the figure supplied by Green (1987) (276 GJ mt^{-1}) for the structurally similar herbicide metolachlor is used.

A number of the insecticides are larger and more complex organic compounds than the fungicides. The pyrethroid ester cypermethrin has for example is attributed an energy value of 580 GJ mt^{-1}, and carbamates such as benomyl (397 GJ mt^{-1}) and carbofuran (454 GJ mt^{-1}) are also energy intensive compounds. Where there is no energy figure available for a particular compound, a judgment was made based on the relative size and complexity of the organic molecule, or similarities between it and substances for which values have been published.

Mila i Canals (2003) uses the average insecticide value (214 GJ mt^{-1}) from Green (1987) as a default figure. Buprofezin appears to be based on a napthalene or quinone intermediate, so a figure in the same order as the average fungicide is reasonable.

The insecticide indoxacarb was attributed an average of cypermethrin, benomyl and carbofuran (477 GJ mt^{-1}). Mila i Canals (2003) uses the default (average) value for lufenuron, but the complexity of the molecule suggests that a higher figure is more appropriate, so a value of 300 GJ mt^{-1} is used. The same figure was attributed to the moulting hormone agonist tebufenozide, and the plant growth regulator N6-Benzyladenine. The chloronicotinyl.substance thiachloprid was attributed the lower average value (214 GJ mt^{-1}).

The macrocyclic lactones are derived from natural products, so despite being extremely complex molecules, they are attributed the average default value. This judgement is again based on the assumption that efficient microbiological processes can be used to manufacture these compounds or their intermediates. The avermectins also manufactured using fermentation processes, and the default figure (214 GJ mt^{-1}) was used. This figure is also used for streptomycin, gibberellic acid, ethphon, aviglycine and the organic garlic and pyrethrum insecticides, although these substances deserve closer attention. The same value is attributed to the viral substance Cydia pomonella granulosis.

The energy content of inorganic chemicals, particularly the inorganic coppers, is based on the energy required to mine and process raw minerals. Poe (2003) offered a value of 219 GJ mt^{-1} for copper oxy-chloride, and this figure was used as the default value for inorganic copper fungicides.

Formulation Packaging and Transport

The energy content attributable to a product's formulation, packaging and transport must also be allowed. Green (1987) offered separate calculations respectively for emulsifiable oils, wettable powder or for granules or dust. The value for miscible oil is used for all "wet" formulations, including emulsifiable concentrates, soluble concentrates and solutions.

In this study the equation for product energy was derived thus:

Product energy (per kg or litre of product) equals (energy attributable to manufacture of active ingredient) x (concentration) plus (energy attributable to formulation, packaging and transport).

Appendix III: Statistical analysis

III.I Descriptive statistics for selected energy intensity variables (generated by Minitab software)

Variable	Mean	SE Mean	Std Dev	Min	Q1	Median	Q3	Max
Ha	16.49	3.46	20.76	0.75	3.85	8.0	17.75	75.9
Kg ha^{-1}	41337	2672	16034	6878	28858	44255	52334	78617
Electrical GJ ha^{-1}	5.031	0.533	3.198	0.0	4.623	5.03	5.03	20.65
Direct GJ ha^{-1}	23.84	2.27	13.63	2.3	12.55	20.8	33.5	65.9
Fertiliser GJ ha^{-1}	9.897	0.551	3.306	2.7	9.9	9.9	9.9	25.2
Urea GJ ha^{-1}	2.015	0.573	3.437	0.0	0.0	0.525	2.178	12.53
Agrichemical GJ ha^{-1}	9.93	1.33	7.96	2.3	6.10	9.9	9.9	46.9
Indirect GJ ha^{-1}	21.84	1.51	9.09	9.3	18.65	19.8	22.53	56.8
Capital GJ ha^{-1}	21.21	1.18	7.07	8.2	21.2	21.2	21.2	49.7
Total MJ ha^{-1}	66.93	3.55	21.31	38.3	51.75	63	74.2	134.9
Total MJ kg^{-1}	1.961	0.197	1.181	.66	1.188	1.610	2.438	6.86
Fuel GJ ha^{-1}	18.82	2.18	13.06	1.6	7.55	15.65	29.8	59.2
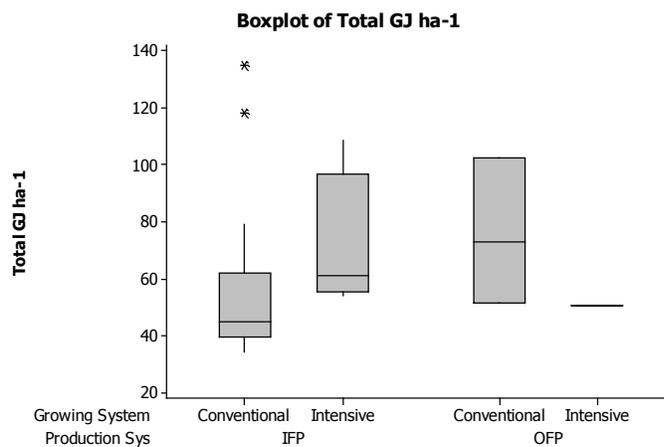
III.II Boxplot showing overlap of total energy intensity by growing system and production system. No significant differences were found.

Boxplot of Total GJ ha-1
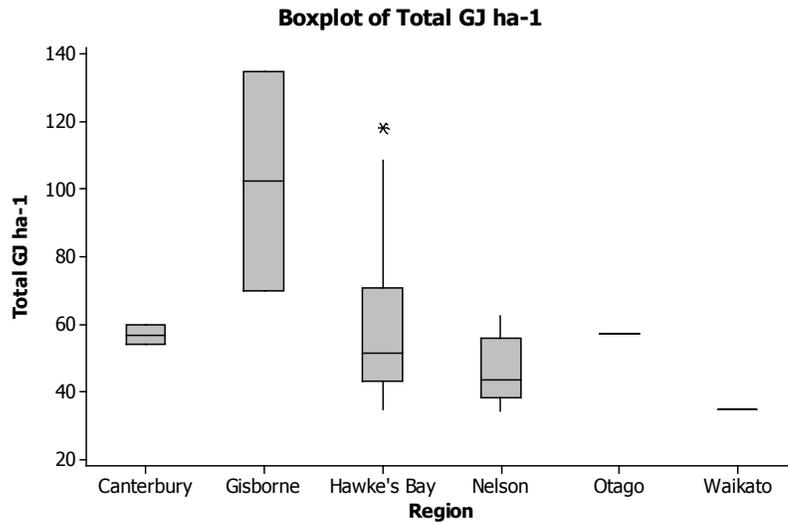
III.III Regional differences. Statistical analysis of energy intensity (per area) showing the Gisborne result as a significant regional difference.

One-Way Normal ANOM for Total GJ ha-1
Alpha = 0.05
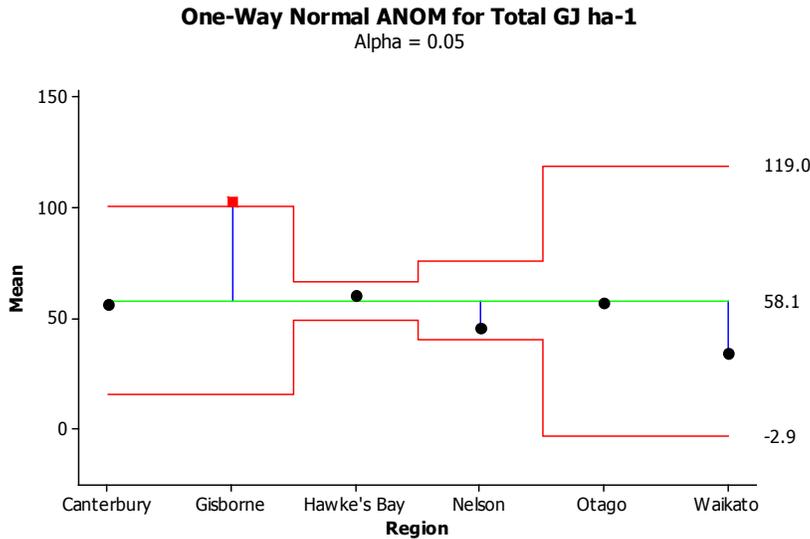
III.IV One way ANOVA of GJ ha^{-1} v ha (no significant trend)

```
Source  DF   SS   MS   F    P
Ha    29  16155  557  0.78  0.703
Error  6  4277  713
Total  35  20432
S = 26.70  R-Sq = 79.07%  R-Sq(adj) = 0.00%
Individual 95% CIs For Mean Based on Pooled StDev
Level  N   Mean  StDev  -----+---------+---------+---------+----
 0.75  1  134.86    *                   (---------*----------)
 0.86  1  53.86     *    (----------*----------)
 1.46  1  59.80     *      (----------*----------)
```

```
1.50  1   56.91      *      (---------*----------)
2.00  1   44.26      *   (----------*----------)
3.00  2   59.29 28.14      (-------*-------)
3.80  2   75.91 45.92         (-------*------)
4.00  2   58.09 10.86       (-------*------)
5.53  1   42.43      *   (----------*----------)
5.67  1   38.34      *   (---------*----------)
6.10  2   94.15 34.25            (-------*------)
7.00  1   62.05      *      (----------*----------)
8.00  3   44.85  6.55        (-----*------)
9.00  1   43.29      *   (----------*----------)
9.50  1   34.38      * (----------*----------)
10.60 1   34.50      *  (----------*----------)
11.00 1   39.69      *   (----------*----------)
13.30 1   44.15      *   (----------*----------)
14.50 1   46.48      *    (----------*----------)
15.00 1   62.22      *       (----------*----------)
17.00 1   43.01      *   (----------*----------)
18.00 1   73.06      *          (----------*----------)
25.20 1   60.89      *       (----------*----------)
33.00 1   61.01      *       (----------*----------)
33.23 1  102.29      *                (----------*----------)
35.00 1   34.70      * (----------*----------)
54.93 1   68.15      *         (----------*----------)
64.90 1   49.92      *    (----------*----------)
69.00 1   53.64      *      (----------*----------)
73.00 1   36.82      * (----------*----------)
                     -----+---------+---------+---------+----
                         0        60       120      180
Pooled StDev = 26.70
```
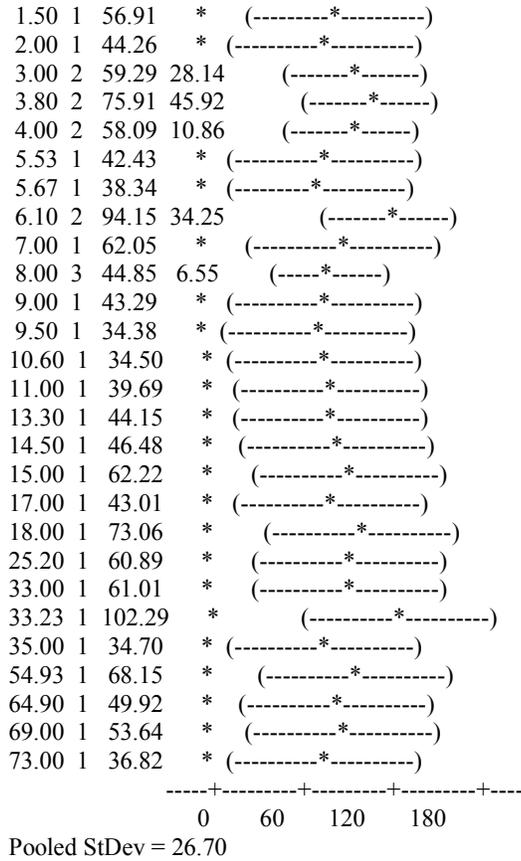
III.V Normality test for direct energy intensity (per area). The normality test for the direct energy inputs (with an alpha level of 0.1) required the deletion of an outlying point to achieve a normal distribution.
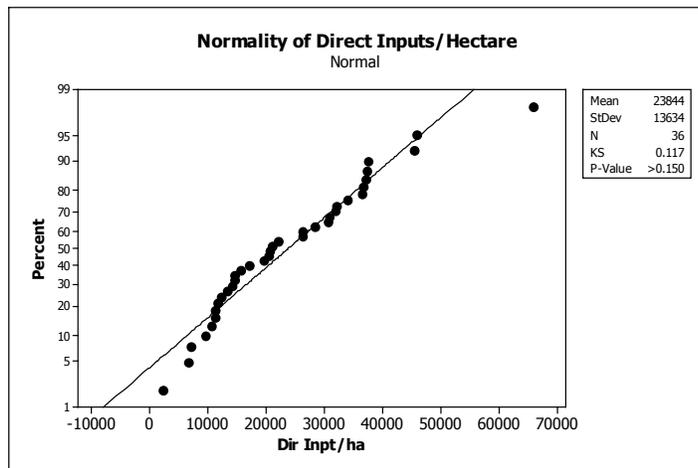
III.VI Analysis of energy intensity of OFP and IFP agrichemical inputs. The bracketed confidence levels below do not overlap, demonstrating a significant difference between the energy content of OFP and IFP agrichemical inputs.

Test - One-way ANOVA: Agrichemical MJ ha^{-1} versus Production System

```
Source             DF     SS          MS        F      P
Production Sys  1   843831127   843831127   20.81  0.000
Error          34   1378613532  40547457
Total          35   2222444659
```

S = 6368   R-Sq = 37.97%   R-Sq(adj) = 36.14%

Individual 95% CIs For Mean based on pooled StDev

```
Level  N   Mean   StDev   --+---------+---------+---------+-------
IFP    32   8230   2516    (---*--)
Org     4  23636  19852                    (--------*--------)
                          --+---------+---------+---------+-------
                          7000    14000    21000    28000
```

pooled StDev = 6368

III.VII Analyses of second-order relationships. Note: the outlying data point HB-17 has been removed from these analyses.

Regression Analysis: Total MJ kg-1 versus Total GJ ha-1

The regression equation is:
Total MJ kg-1 = 0.685 + 0.0149 Total GJ ha-1

```
Predictor         Coef   SE Coef   T     P
Constant         0.6852  0.2902  2.36  0.024
Total GJ ha-1  0.014900  0.004579  3.25  0.003
```

S = 0.645475   R-Sq = 24.3%   R-Sq(adj) = 22.0%

Analysis of Variance

```
Source          DF    SS       MS      F      P
Regression       1   4.4115   4.4115  10.59  0.003
Residual Error  33   13.7491  0.4166
Total           34   18.1606
```

Regression Analysis: t ha^{-1} versus kg MJ^{-1}

The regression equation is:
t ha-1 = 19.5 + 28.7 kg MJ-1

```
Predictor   Coef   SE Coef   T     P
Constant   19.480   4.243  4.59  0.000
kg MJ-1    28.680   4.882  5.87  0.000
```

S = 10.5817   R-Sq = 51.1%   R-Sq(adj) = 49.6%

Analysis of Variance

```
Source          DF    SS      MS      F      P
Regression       1   3864.7  3864.7  34.51  0.000
Residual Error  33   3695.1  112.0
Total           34   7559.8
```

Regression Analysis: t ha-1 versus Total MJ kg-1

The regression equation is
t ha-1 = 62.9 - 13.4 Total MJ kg-1

Predictor   Coef SE Coef   T   P
Constant   62.928   4.613 13.64 0.000
Total MJ kg-1 -13.360   2.684 -4.98 0.000
S = 11.4390   R-Sq = 42.9%   R-Sq(adj) = 41.2%

Analysis of Variance
Source   DF   SS   MS   F   P
Regression   1 3241.7 3241.7 24.77 0.000
Residual Error 33 4318.1   130.9
Total   34 7559.8

III.VIII Analysis of indirect energy intensity

The analysis of means demonstrates significant difference (95% confidence) between
IFP and OFP indirect energy intensity (by area), but not by crop. No significant
difference was found between intensive and conventional indirect energy intensity.

One-Way Normal ANOM for Agrichemical GJ ha-1
Alpha = 0.05
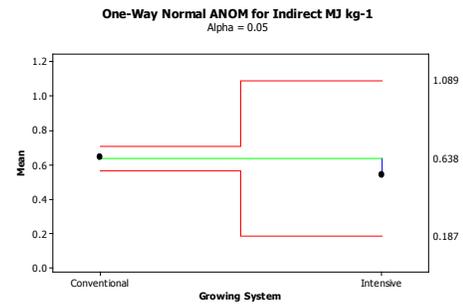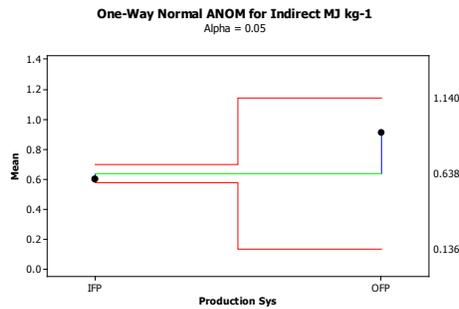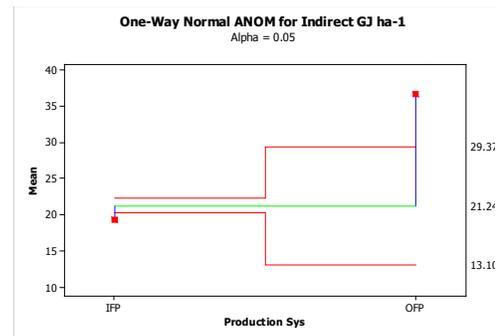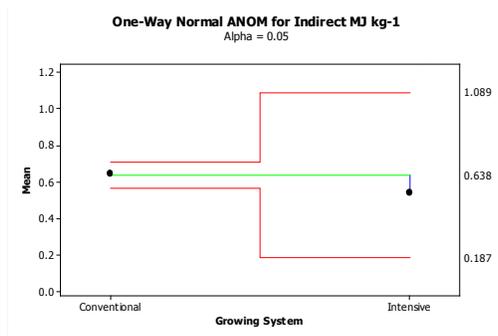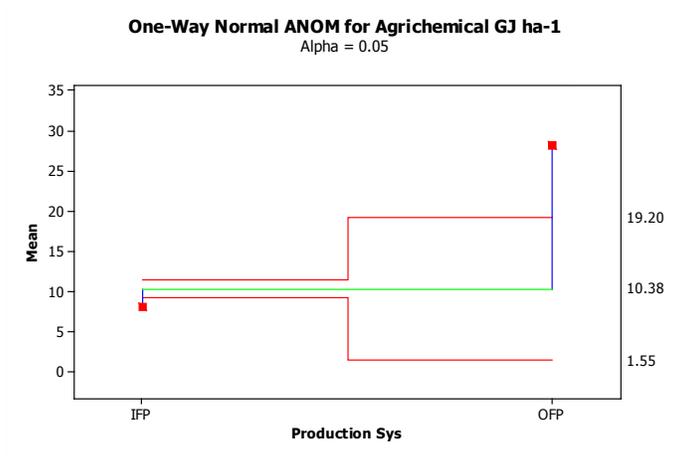
Agrichemical energy intensity analysis contd. (III.VIII)

III.IX Shipping analysis (Ship speed vs length)

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	48.638	48.638	13.03	0.001
Residual Error	47	175.467	3.733		
Total	48	224.105			

Unusual Observations

Observation	SQRT	LOA	Speed knts	Fit SE	Fit	Residual	St Resid
6	19.2	19.800	24.515	0.459		-4.715	-2.51 R
8	18.7	19.000	24.226	0.398		-5.226	-2.76 R
39	15.2	18.000	22.202	0.389		-4.202	-2.22 R
41	14.1	16.500	21.500	0.544		-5.000	-2.70 R
49	13.0	20.500	20.895	0.693		-0.395	-0.22 X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large leverage.

Appendix IV: Model block for irrigation, and non-machinery capital items

The survey established capital energy inputs for machinery and plant. The items of capital energy that were not surveyed were estimated from a theoretical model orchard equivalent to the mean size of survey respondents. The items that were estimated from this model were:

-Reticulated irrigation systems

-Posts and wires

-Buildings

-Tracks and loading areas

Inventory of materials in 1ha irrigation block.

Introduction

Pimentel (1980) provided a value 1764 MJ yr^{-1} for an installed sprinkler system. To estimate the energy embodied in New Zealand orchard irrigation systems a model orchard was developed, based on the mean area of orchards in the energy survey.   To develop this model, we needed to briefly review the factors that influence the layout of an orchard from an irrigation perspective.

The dimensions of an irrigated unit in an apple orchard are constrained by historical factors such as legal boundaries and existing irrigation layout as well as production criteria. The block dimensions and tree spacing are further constrained by current technology (such as the characteristics of an existing pump and bore) and historical decisions made for obsolete varieties and different markets. Choices of variety and layout are strategic in nature, as the grower has to make a commitment that will affect the profitability of the orchard over the ensuing years or even decades. Irrigation systems are to a large extent site specific, but they also reflect the total growing regime – the sum of the strategic choices made by the grower.

It follows that irrigation design specifications for a model block cannot be claimed to be standard or average. At best they can be regarded as 'typical'. In the present survey, the growers were simply asked to report if their orchard had a reticulated irrigation system. If the answer was no, then the capital energy inputs for irrigation were assumed to be contained in other plant within their inventories. If the answer was yes, energy values are based on the model developed here.

Planting Density

The density of trees in conventional plantings ranges from around 400 trees ha^{-1} (at 5 m x 5 m plantings) to around 1500 trees ha^{-1} (at 1.5 m x 4.5 m). Intensive plantings using dwarf trees could achieve much higher planting densities, such as 2700 trees ha^{-1} (at 1.5 x 2.5 m). These figures are quite conservative, and don't reflect very low densities of older orchards with large trees on vigorous rootstocks, or the very high densities of some developing intensive technologies. For the purposes of my model, a planting density of 1000 trees ha^{-1} has been arbitrarily selected, although the model can be adjusted to test its sensitivity to other densities.

Model layout

The model developed here considers a theoretical 100 m square, 1ha block in the context of a 400 m square, level, 16 ha. planted area, 16.5 ha total area (the mean orchard area in the present survey was 16.5 ha). Fig IV-1 shows the layout of the theoretical block.

Mainline.

The irrigation main-line is sized in accordance with hydraulic principles. The design specifications of an actual system are determined by the size and characteristics of the pump and bore, the contours of the land and the distance of the plantings from the bore. The design will also reflect the needs of the crop, the soil type and water quality. If the pump and bore are already in place, as is the case in a redevelopment situation, then the specifications of the design are constrained by the output of the pump. In this case, we have specified a pump supplying 36 m³ per hour at 6 bar.

Example from survey respondents

An example similar to my model is found on orchard HB-1, where one of its three bores (supplying about 20 ha) supplies sufficient water to irrigate areas of 1.1 ha to 1.3 ha at time. Each irrigation block requires a flow rate of approximately 40 cubic metres per hour. This flow rate can deliver 6 mm per hour. If we assume a soil moisture capacity of 50 mm (equivalent to a light silt loam soil), then this irrigation design can replenish about half the soil moisture capacity (24 mm of water, to 16 irrigation stations) in 64 hours of continuous running. The relevance of this example is that it provides a real example for comparison with my mean orchard size. Although the soil type in HB-1 (Takapau silt loam) is arguably at the light end of the range on which apples are grown in New Zealand, the irrigation system is reasonably typical for orchards with reticulated irrigation systems in Hawke's Bay.

The total length of mainline in my model is 1000 m. Each hectare can be apportioned 62.5 m of mainline. A mainline size of 100 mm is adopted in this model. (The 100 mm mainline incurs a headloss of 1.4 bar 1000 m^{-1}, which is well within my design requirements.) The dimensions of the mainline are the only variables in my irrigation model that change with increasing orchard size.

The irrigation system design is constrained by the planting density, but many of the components of the system would not be significantly altered for a range of planting densities. System designers may however incorporate an element of over-design to allow flexibility for future changes. (The mainline in my example HB-1 is sized at 150 mm, which is clearly over-designed for the immediate needs, however this over-sizing provides flexibility to extend the area served by this bore in the future.)

Each hectare block in my model is served by a sub-mains (the pipe on the downstream side of the supply valve). This model allows 105 m of 65 mm sub-mains for each hectare. These allowances apply to all planting densities. Allowing a conventional row spacing of 4.5 m, my 100 m square block will have 22 rows, or 2200 m of lateral pipe. The same sized block with 3.5 m spacing (representing an intensive regime) will have 28 rows, or 2800 m of lateral. My model is planted at 1000 trees ha^{-1}, a spacing of 2.2 m.
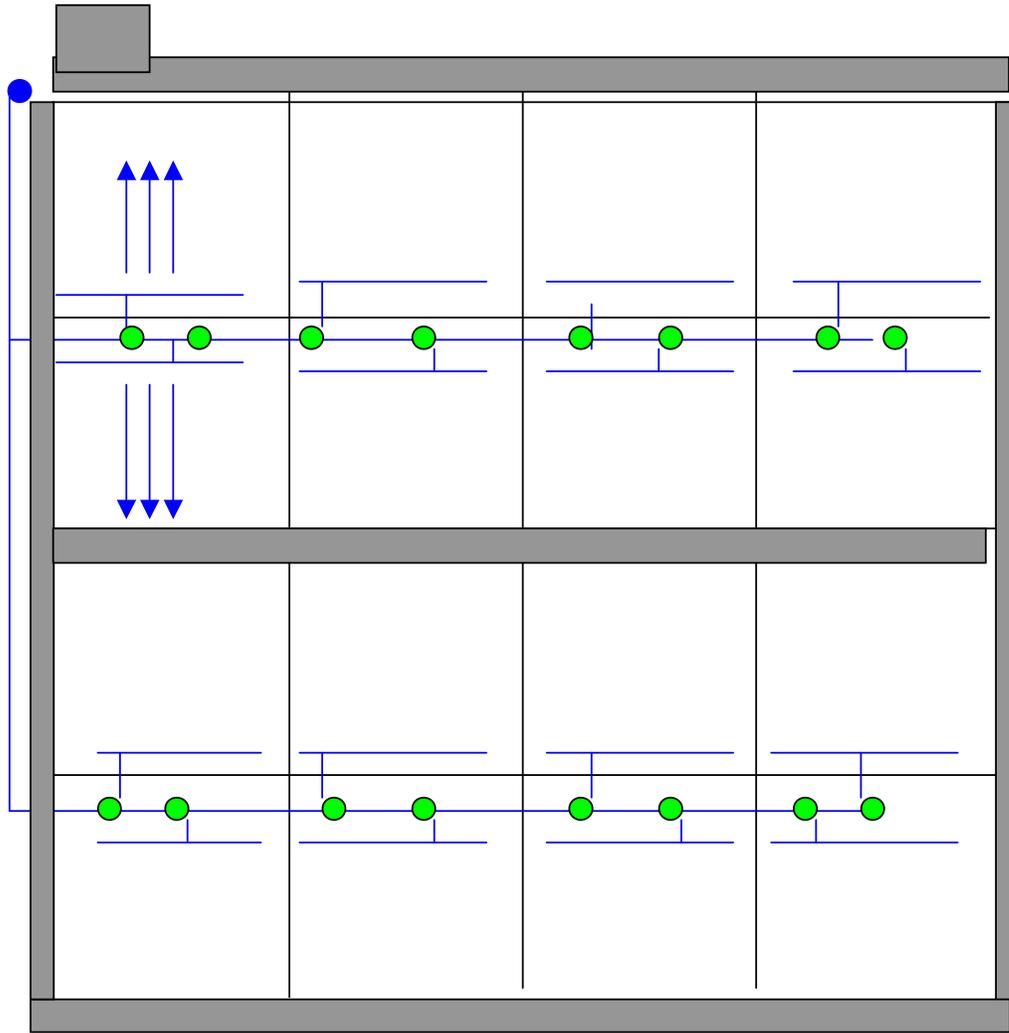
Figure 4.1 Model irrigation block (Previous page)

●   Bore

●   50mm valve

_____   PVC mains and submains

⟶   19mm lateral pipe

▭   Headlands
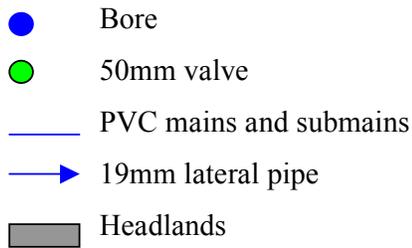
Each small square represents one 100m square 1ha block. Each block has 22 rows spaced at 4.5m.

Valves and fittings

In my model, the one hectare block is supplied through a solenoid activated 50 mm bronze Bermad 400 series 2 inch valve (weighing 4 kg), which operates in the desired range (with a headloss of 0.45 bar at 40 cubic metres per hour). The pipes and valve were assembled using moulded PVC fittings (such as elbow, tees and reducers). This model allows 10 fittings per ha. The model adopts pressure-compensated emitters, supplied by 19 mm lateral pipe.

Electric wire

Electric solenoid irrigation valves are activated by low voltage current distributed in underground plastic sheathed copper wires (typically 1.5 mm diameter). Each valve requires a single wire of the same distance as the mainline plus a common, or return wire of heavier gauge (typically 2 mm). Alternative systems using hydraulic tubes or wireless systems do exist, so the selection of an electrically operated system is an arbitrary choice. The length of wire allocated per hectare is 62.5 m of each diameter (as per water mainline).

Wire mass

1.5 mm	1.64 kg 100 m^{-1}	1.03 kg
2.0 mm	2.96 kg 100 m^{-1}	1.85 kg
total wire ha^{-1}		2.88 kg

Emitter

Emitters are spaced to supply the root zone of the tree, without wasting water on the grassed sward. The spacing of the emitters is ideally designed to correspond to the tree spacing (either one emitter per tree, or one emitter between two trees). In my model, the option of one emitter per tree is selected. The emitter selected is a Dan 2001 pressure-compensated sprinkler that supplies 36-38 l hr^{-1} between 1.5 and 4 bar pressure.

Maintenance costs

Irrigation systems conform reasonably closely to Pimentel's model for machinery. Although underground components are not subject to physical wear, they do fail from time to time, due to pressure fluctuation, ground movement, root impingement and damage from machinery or animals. Those parts of the system above ground are even more susceptible to damage. Machine based orchard operations are characteristically high in kinetic energy. When these operations are conducted repeatedly in close proximity to soft or brittle components, the attrition rate of those components is understandably high. An example is the damage sustained by the pipework around valves from stones flicked by mowers. Laterals and sprinklers are similarly vulnerable. The valve bodies are robust, but their components are subject to physical wear and corrosion.

This section of the study is necessarily based on anecdotal evidence rather than the actual records over two or more decades that would be necessary to provide definitive figures, however it can be argued that Pimentel's machinery model provides a reasonable basis for estimating the energy required for repairs relative to the energy expended in the manufacture of the components.

Irrigation embodied energy values

The value calculated for this block based on Pimentel's methodology for machinery and plant was 2928 MJ ha^{-1} yr^{-1} (compared to 1764 MJ ha^{-1} yr^{-1} from Pimentel (1980)). This figure is sensitive to the lifetime assumed for lateral pipe. Pimentel offers a value of just 10 yrs for the lifetime of lateral pipe. The lifetime assumed in this model is 15 yrs. If a value of 20 yrs is used, the energy value is 2492 MJ ha^{-1} yr^{-1}. On the other hand, if the model were based on an intensive production regime, the energy value would increase in proportion to the increase in total row length. If we

consider the likelihood that Pimentel's value was based on a lower planting density (typical of US plantings of that period), then the value offered here is consistent with his value.

The energy content of other capital items follows the early methodology of Pimentel (1980), which forms the foundation for the Dairy energy study (Wells, 2001) and the kiwifruit study (Barbour, 2001). The energy co-efficients used include intrinsic energy plus manufacturing and maintenance energy. The annual energy cost is calculated by assuming a straight-line depreciation over an estimated working life.

Tracks, headlands and loading areas

My model is provided with a minimum area of graded tracks based on a 7metre headland at each end of 200 metre "runs", and a 5 m vehicle width along the two outside rows. An additional loading bay of 50 m by 30 m is allowed. The total graded area is 13900 m^2. This area is assumed to be partly contained within the 16 planted hectares. The total area of the orchard is 16.5 ha, the mean of my study.

Assuming a depth of aggregate of 0.15 m and a bulk density of 1500 kg m^{-3}, a volume of 2085 m^3 results, with a mass of 3128 tonnes. The energy content of this aggregate is 312800 MJ (Wells, 2001). For comparison, Barbour (2001) allows just 810 m^3 for a 41 ha kiwifruit block. However, he also allows a 15 m^3 annual input. The value of 0.1 MJ kg^{-1} provided by Wells (2001) contains a maintenance component, so no further allowance is required in this model. The lifetime of the tracks and loading areas used in this study is 30 yrs, resulting in an annual energy cost of 632 MJ.

Buildings

There is no absolute requirement for buildings on an orchard other than the health and safety requirements for workers. Even toilets and bathroom facilities can be provided as temporary portable units during harvest. However, most orchards have some sort of structure as a lunchroom for workers, and some workshop facility for maintaining machinery. My model allows a 50 m^2 building for staff, and another 50 m^2 building as a workshop.   The energy value of a service building of this area is 176780 MJ

(Pimentel 1980). As a comparison Barbour (2001) uses values of 600 MJ m^{-2} for implement sheds, and 2000 MJ m^{-2} for an office area.

In this study a working life of 30 years is used for buildings. Wells (2001) uses a working life of 20 years for dairy sheds. This lower value reflects the technological content of dairy sheds, whereas orchard buildings are required for simple operations such as storage and shelter, and a longer working life is justified. The energy cost attributable to buildings in this model is 357 MJ ha^{-1} yr^{-1}.

Posts and wire

My model assumes a post spacing of 10 m, with end assemblies requiring equivalent timber of four ordinary posts. An energy cost of 9 MJ is allowed for each post, resulting in an energy content of 3366 MJ ha^{-1} for posts.

Wire is estimated on the basis of a three wire system. Each hectare contains 6700m of wire. The energy value for galvanized 2.5 mm high tensile wire is 1.3 MJ m^{-1}. The energy value is 8710 MJ per hectare.

A working life of 20 yrs is used. This assumes that post and wires can be recycled through at least one replanting cycle. In comparison, Wells (2001) uses a working life of 25 years for boundary fences, and 15 years for internal fences. The total energy value attributable to posts and wires is 12076 MJ ha^{-1}. The annual energy cost is 604 MJ.

The annual energy input attributable to the components of this model are:

Irrigation   2928 MJ ha^{-1}
Buildings   357 MJ ha^{-1}
Posts and wire   604 MJ ha^{-1}
Tracks   632 MJ ha^{-1}

Appendix V: A Report on the Utilisation of Biomass to Offset Energy Inputs in Apple Production

New Zealand is a primary production economy that has traditionally depended on its ability to export food to Northern Hemisphere markets. New Zealand food products have earned a reputation in those markets for reliability. Awareness of global climate change has recently been viewed as a threat to this economy, as our distance from our markets has been perceived as an impediment to achieving sustainability criteria. By adopting carbon recycling technologies New Zealand primary production can move toward confirming market perception of its exported food products as reliable, verifiable and ethically justifiable from social and environmental perspectives.

This report focuses on opportunities for utilising waste biomass in apple orchards. It looks at mechanisms for improving productivity and optimising the energy and carbon balance within the product lifecycle. Conclusions are derived from benchmark energy indicators for New Zealand apple orchard production developed from a survey of New Zealand apple production.

Climate change and anthropogenic global warming claims are characterised by a level of consensus in the scientific community, but not without dissenting voices. Arguments in the present paper are built on the assumption that food production industries need to respond to the global imperative to reduce greenhouse gas (GHG) emissions. Where possible, strategies that are consistent with non-contentious sustainability objectives, such as reduced dependence on fossil fuels and enhanced soil nutrition are identified. Strategies that depend on the current political environment are treated as short-term economic opportunities.

Biomass is organic material derived from living tissue. The components of wood biomass are hemicellulose, cellulose, lignin, organic extractives and inorganic minerals (Mohan, 2005). The energy content of biomass results from its stable carbon bonds that release energy when broken. In this report the concept of exergy is occasionally used in preference to energy to distinguish the useful energy that can be released from biomass from the embodied energy that represents the sum of energy

inputs in the production process. Apaiah (2005) defined exergy as "the maximum amount of work that can be extracted from a system".

The potential energy of biomass is achieved through the capture of solar radiation via photosynthesis, a process that is enabled by direct, indirect and capital energy inputs within the production process. The "embodied energy" within the biomass is not recoverable, as much of it has already been lost to the environment in preceding processes. However, without the production processes, and their associated inputs, the capture of solar energy through photosynthesis would not occur. The energy indicators "energy intensity", "energy input" and "energy ratio" referred to in this report are conventional terms referring to the ratios of embodied energy to land area and crop production. The term "energy density" is typically defined as the energy stored in a given system per unit mass or volume, however in the present context it is more clearly defined as the ratio of exergy to mass.

In agricultural production, the energy required to produce the crop is accounted as energy inputs that are embodied in the production crop. This is a reasonable assumption if all the energy in waste biomass is lost to the environment. If surplus biomass is treated as a source of carbon and exergy, energy recovered from that biomass can be calculated as a credit against the embodied energy of the primary crop, and sequestered carbon as a credit against carbon emissions.

The primary source of surplus biomass in New Zealand apple production is pruned material from crop trees. Other potential sources of biomass are pruning slash from shelter trees, entire crop trees periodically removed for redevelopment, clippings from the grass sward, waste fruit and co-produced crops. Some technologies can potentially also utilise plastic waste materials as a carbon and energy source. (Although plastics are invariably carbon compounds, and hence organic, they fall outside the definition of biomass). The conclusions of this study are confined to the energy available from pruned material.

Italian researchers examining the energy characteristics of pruning residues (Malavasi *et al.*, 1983) measured the mass of pruned material in sixty orchards and vineyards, and calculated the associated energy outputs. The present study examined the energy

and carbon recoverable from the biomass with respect to developing technologies. While there are differences between Italian growing practice c1983 and current New Zealand practice, there are arguably enough similarities to adopt the study as a useful benchmark. Modern growing practices seek to minimise vegetative growth, so the Italian estimates could exceed those of New Zealand. The actual volume of pruning material achieved is site, season and variety dependant, as well as being influenced by management practices. However, while many crop production practices have been improved in the last two decades, the basic vegetative potential of apple trees, and the soil and climatic conditions under which they are able to be grown has not altered significantly over this period. The Italian study identified some rootstocks from the study that are extant in current New Zealand production, including M106, M 9, and M 26, and describes planting densities that cover similar ranges to typical New Zealand production regimes.

Malavasi, *et al*. (1983) reported an average of 4.9 t ha^{-1} of pruned material gathered from apple trees. The study compared the volume of wood required to feed heating boilers with an equivalent volume of oil, and reports the production areas required to achieve this. While modern technologies offer a variety in treatment mechanisms, the study provided a useful benchmark for energy calculations. The report equated the energy available from the combustion of 28 t (gathered from 5.7 ha) of dry wood with the energy available from 5.25 t of oil, an energy value of 41.45 GJ ha^{-1} (reported as 0.99 tep ha^{-1}). Using average values for hardwood (moisture content 12%) reported by Boustead and Hancock (1981), 4.9 t of pruned material has an energy content of 84.3 GJ. This energy value is equivalent to 1805 l of diesel (assuming an energy value for diesel of 46.7 MJ l^{-1} (Wells 2001)) and a relative density of 0.86.

It is apparent that a different set of assumptions are used in the Italian report, with either a lower value for the energy content of the wood being adopted (approximately 10 GJ t^{-1}) or a different set of assumptions for the energy content and density of fuel oil. However the key finding is the 4.9 t ha^{-1} of pruning wood. The energy value for wood reported by Boustead and Hancock (1981) is cited in subsequent energy studies (Dalzell, 1994).

In the Italian study, energy was reported as heat released directly from biomass through combustion. Unfortunately heat is of limited use in New Zealand orchard production, although when heat is required the combustion of biomass is a relatively efficient process. A drawback to the combustion reaction is that carbon is released into the environment. If carbon (in the form of fossil fuels) is used in an agricultural processes generating that biomass, there would be a net emission of CO_2 to the environment.

Biomass can be regarded as a medium for the storage of energy and carbon. There are a few key objectives in seeking to process biomass to other forms. Society has invested in the development of technologies for making use of energy dense substrates (fuels).   The usefulness and value of these substrates is determined by their energy density and their state, composition, purity and location. A report on forest residue harvesting for biofuel (EECA, 2007) showed an inverse linear relationship from 5.5GJ t^{-1} to 19GJ t^{-1} over a corresponding moisture content of 65% to <5%. Although this report was in the context of bio-oil production, the general principle applies to other wood-fuel processes. Large wet logs are of lower value than small dry logs. Pellets are possibly the optimum solid conformation, preferred to chips and sawdust. Gas is useful, but requires special vessels to contain it. Mixtures of gasses (like LPG) can be as useful as pure compounds. Liquid fuels have proven to be the most useful and most versatile, and as with gases, liquids formed from mixtures of compounds have proven to be ideal fuels.

The relative value of liquid, gas (and pellet or powder) fuels rests in the cost and ease with which they can be transported and converted into work. This variable value reveals a hidden assumption – that a fuel is most valuable when it is spatially near to the point at which it can be transformed into useful kinetic energy. Therefore the first objective in processing biomass is to generate substrates in a stable, energy dense, transportable form. If a fuel can be used *in situ* to achieve other objectives, then the life cycle costs contained in subsequent processes (including transport) can be circumvented. This principle is demonstrated in the relative efficiency of demand-side improvement initiatives in electricity distribution systems compared to supply-side initiatives (Cleland, 2005).

The present awareness and global focus on climate change has created a second objective – that of reducing GHG emissions in the whole life- cycle of a product. The most significant GHGs from agricultural processes are CO_2, CH_4 and N_2O (IPCC 2007). The most important of these is CO_2. If a process can be designed to be carbon neutral, or carbon negative, environmental and economic benefits are realised. Two avenues for achieving a reduction in carbon emissions are considered: to replace some of the fossil fuel inputs into the production system with carbon cycled from the process itself, and to sequester carbon into long-term storage at points within the process.

The objectives for using surplus or co-produced biomass in apple production are:
- To transfer the potential energy contained in biomass into kinetic or heat energy in mechanisms that substitute non-renewable energy inputs and fossil fuel carbon inputs into the apple production value stream.
- To process the biomass into more versatile and transportable energy dense substrates (that can substitute non-renewable energy or carbon inputs into the wider system).
- To sequester carbon into long-term storage to offset non-renewable inputs elsewhere in the value stream.

Alternative processes
Low temperature (LT) pyrolysis:
- Low temperature pyrolysis is a relatively accessible technology. The process is exothermic to the extent that surplus energy may be available for other applications (at the expense of biochar yield)
- The process is carbon negative if biochar is sequestered
- The process offers soil enhancement, and fertiliser substitution benefits

Disadvantages and barriers to LT pyrolysis of pruning residues:
- The processing of prunings requires either chipping (in place, as with current mulching systems) or following physical extraction from the tree rows. Both processes are moderately energy intensive.
- A biochar pyrolyser would need to be either purchased as a collective district asset, or developed on a small scale for availability to individual growers.

- The required depth of injection into soil, and a mechanism for achieving this in an apple orchard situation are not known

Addressing the disadvantages and barriers:

- Processing pruning material is an issue already, and any proposed new mechanism can be compared to the energy intensive practice of mulching. There may be enough surplus energy available through the pyrolysis process to drive or at least support the mechanical breakdown of tree limbs. This implies an in-situ process, and is a long-term solution that assumes the development of suitable technology.

-Suitable pyrolysers already exist, or could be constructed using known technology.

-An interim soil injection process would involve spreading the biochar with fertiliser spreaders, and cultivating it into new plantings as part of the redevelopment cycle.

Gasification- Gasification is a high temperature reaction (>700C) achieved by heating a carbon source in a controlled low-oxygen atmosphere producing either a hydrogen/ CO mixture (syngas), or "producer gas" which contains 42% nitrogen. This reaction offers a variety of energy rich fuel products, namely: methane, methanol and hydrogen, and synthetic fuel via the Fischer-Tropsch process. Gasification oxidises all the carbon in the carbon source. If fuel products are subsequently burned, the carbon is emitted as CO_2, however, if the fuels replace fossil fuels the overall process is carbon neutral, and represents net movement toward sustainability.

Gasification is a series of reactions that can be manipulated to provide a variety of products, or product mixes. Various configurations of plant are described by Bridgewater *et al*. (1999). One opportunity represented if this process is adopted by the New Zealand apple industry is that other carbon sources (including plastic containers) can be used as feedstock. The gasification of plastics is considered an environmentally clean method of disposal, and while it introduces a fossil fuel based carbon source to the system, it can be argued to be more sustainable than disposing of plastic in landfill. Another advantage for the apple industry is that synthetic diesels are achievable as an end product.

Gasification is a mature technology, having been widely adopted during fuel shortages in WWII to power vehicles. However, it has been re-visited relatively

recently, with a revised design for a more efficient gasifier (the stratified downdraft gasifier) being published in the late 1980s (Reed and Das, 1988).

Gasification Summary

Gasification is a technology that offers flexible energy and carbon outcomes. The production technologies are mature and well understood, and represent a step toward sustainability.

Bio-oil - The production of bio-oil requires fast medium temperature pyrolysis of biomass, followed by condensation of the resulting vapour. The energy balance of bio-oil production depends on the characteristics of the feedstock and the production technology, but a representative energy balance (Mohan, 2005) reports inputs of 8755 BTU / lb and outputs of 21200-27000 BTU / lb from pine bark/sawdust. The EECA report (EECA, 2007) reports recoverable energy densities up to 19 GJ t^{-1} from forestry residue. The technologies are currently the subject of intense research, and the field is attracting considerable academic enquiry and commercial investment. Overviews of the processes and properties of bio-oil are provided by Bridgewater *et al*. (1999) and Zhang *et al*. (2006). The most significant factors for the present report are:

Bio-oil technologies are regarded as an important component of a sustainable future, and may well provide positive opportunities for NZ apple production.

No single production technology has yet emerged as clearly superior. The scale of commercial plants currently proposed or in place exceeds a viable scale for New Zealand apple production. Any immediate opportunities would depend on transporting biomass to a commercial site based around forestry operations.

Agri-chemicals are not the most important component of energy inputs, but even so the inputs could be substituted using biomass products. Bio-oil is a complex mixture of organic compounds (Zhang *et al*., 2006), some of which could potentially be targeted as intermediates in the production of agri-chemicals. The methodology adopted in the apple orchard energy report above for estimating the embodied energy of agri-chemicals relied on published estimates of the energy content of common intermediates (Green, 1987). Intermediates manufactured from waste by fast pyrolysis could replace those accounted for presently as an energy input to the system. While this might appear to be a relatively minor improvement in energy inputs into

NZ apple production, it is an area that represents a significant uncertainty, as multinational chemical manufacturers do not disclose the processes by which they manufacture their products. Any move toward ownership of the process would reduce this uncertainty, while potentially providing a profitable value stream from waste products. It also offers a potential reduction in the total life-cycle emissions.

It is unlikely that the volumes available from orchard biomass would justify the extraction of chemical intermediates, however these chemicals could potentially be extracted in commercial volumes from other New Zealand primary value streams, particularly forestry (EECA, 2007). If the products were subsequently onsold to multi-national suppliers, then the global fossil fuel energy substitution achieved could be credited to the wider New Zealand production system. Bio-oil production therefore represents a strategic opportunity for the New Zealand apple industry rather than an immediate solution to recycling biomass.

Comparison of pyrolysis processes
The main variables in pyrolysis are reaction temperature, heating rate and vapour residence time. Altering these variables produces reaction products varying from mostly gas, with some char and liquid (gasification), to mostly liquid with some char and gas (bio-oil through fast pyrolysis). The intermediate product group resulting in approximately equal proportions of solid, gas and liquid (carbonisation) is achieved with lower temperatures and long vapour residence times. This process achieves the maximum char yield. The factors that have to be considered by the NZ apple industry in selecting one process over the others are:
- The maturity and availability of the technology (favours gasification, followed by biochar)
- The potential for strategic advantages in sustainability and climate change issues (favours biochar)
- The potential for innovation in product and process (favours bio-oil)

Anaerobic digestion -Anaerobic digestion of carbohydrate results in the production of biogas, a mixture of methane (60-70%) and carbon dioxide, plus small quantities of hydrogen sulphide, nitrogen, hydrogen, carbon monoxide and other impurities. The production of biogas requires a variety of organic inputs, including manure. A

carbon/nitrogen ration of 20:1 to 25:1 must be maintained. Cellulose material needs to be broken down mechanically, and typically undergoes a period of aerobic digestion (composting) prior to anaerobic digestion. Anaerobic fermentation is susceptible to interference from chemicals, notably copper compounds.

Biogas production has been implemented as a nationwide strategy in China, and the construction of biogas pits in rural areas is supported technically and socially (van Buren, 1997). Biogas production achieves many objectives of sustainable food production, producing fuel and fertiliser, and processing waste that would otherwise pollute land and water. Nevertheless there are significant barriers to its introduction as an industry wide solution to energy and waste issues for orchards. These barriers include:
- The cost and difficulty of constructing digesters
- The need to mechanically breakdown and compost plant material before digestion
- The requirement of a nitrogen rich nutrient source
- The requirement to learn the required skills to manage a potentially dangerous gas.
- The adaptation of machinery to run on biogas

All the above barriers can be resolved, as is demonstrated in the Chinese model. Van Buren (1997) observes that the barriers are more social than technical.

Addressing the barriers
The technical barriers to constructing digesters have been solved in the Chinese model in a fashion that suits the ready availability of labour. A satisfactory New Zealand model would probably require a universal design constructed from concrete or roto-moulded plastic, installed and supported by suitably qualified teams. The role played by training and support teams in China could to some extent be replaced with technical monitoring solutions. Breaking down, and pre-composting plant material would require an adaptation of chipping/shredding machinery. This is problematic, as apple wood does not lend itself to feeding hoppers in the manner of long straight woodlot material. Personal safety issues are also challenging. The challenge is to break down wood with a minimum horsepower, indicating a need for highly efficient cutting mechanisms. However, if solutions to these challenges are devised, there are

immediate advantages, not the least of which is that it suits a growing system based around larger more vigorous trees (the majority of existing orchards).

Achieving the correct nutrient balance is not technically difficult, but it would lend itself to a more integrated, multi-tier farming system than is typical for New Zealand orchards. Nitrogen sources include human, animal and possibly aquaculture waste. Social barriers to recycling human or piggery waste shouldn't prevent its use in the orchard situation. One important observation is that the use of copper fungicides in organic farming favours Integrated Fruit Production (IFP) regimes for biogas installations.

Learning new skills should not be a barrier, but the issue is that the skills are outside of the normal skill-set of horticulturalists. In the absence of genuine incentives and in times of low financial returns, the unfamiliarity of the technology is a significant barrier. To address this barrier, some level of industry based incentive is required. Biogas is a proven fuel for vehicles and domestic and small-scale industrial heating. In the short term, the gas would be better managed by fuel companies, rather than used on orchard. It would require less capital investment for orchards to continue to use diesel machinery, and for the recycled carbon to be used as an accounting credit. However, in the long term, a principle can be recognised that the closer to the site of production a fuel can be used, the less opportunity there is for losses.

Biogas summary

Biogas is a proven and accessible technology. Most of the barriers to its deployment as a carbon, nutrient and energy recycling system are able to be overcome. If the technical challenge of extracting, chipping or shredding pruning slash within an energy input equivalent to the output of the biogas plant can be achieved, then the additional bonus of high grade organic fertiliser and the substitution of existing fossil fuel inputs from mulching make the exercise profitable (in a sustainability sense).

Energy, sequestration and nutrient recycling

An argument arises as to whether it is better from a climate change perspective to sequester carbon (through biochar production) or to derive energy from the carbon by gasification, digestion or bio-oil production. An argument can be proffered against

biochar sequestration on the basis that it is inefficient from a systemic perspective. If the production system requires energy inputs from fossil fuel sources, then carbon sequestration is "false economy", as energy losses through the system ensure that the production of carbon for sequestration requires equal or greater amounts of carbon at an earlier stage of the process. Carbon available on site at the final point of use should be worth many times the same mass of carbon in a fossil fuel source, and should be able to be economically converted to a useful energy source. [See Cleland (2005) for a discussion of the relative efficiency of demand-side improvement initiatives in comparison to supply-side improvement initiatives.]

This argument concludes that conversion of biomass to fuel should take precedence over carbon sequestration until all the fossil fuel inputs in the system are replaced with renewable energy sources. However, having stated the principle, the extent to which recycled biomass fuel inputs are genuinely renewable must be closely examined and tested. Hidden systemic inputs, particularly in capital equipment must be examined to reduce the energy required to produce the final product. Systems literature demands that the system boundaries are carefully examined, and explicitly recognised in such a study (Ulrich, 2001).

The argument is further undermined by the benefits accruing from biochar as a soil enhancement. These benefits can be stated qualitatively as enhanced crop production relative to energy inputs. The potential advantages are twofold – production is more efficient and carbon sequestration through photosynthesis is increased. Strategic decisions should distinguish between the political benefits of supporting climate change initiatives, the short term economic benefits derived from carbon trading and long term economic benefits derived from independence from unreliable or volatile fuel and energy sources, and improved productivity resulting from soil enhancement. A significant conclusion is that biochar production, gasification and biogas or bio-oil production would each constitute an improvement to the status quo.

Most of the options discussed above provide an opportunity for recycling nutrients, or in the case of gasification, capturing nitrogen. Biogas production results in a nutrient rich slurry that is used as an organic fertiliser in the Chinese model. Anaerobic digestion is claimed to conserve nitrogen, and make it more available to plants than

raw manure. However biogas production is ideally suited to a multi-tier system, such as systems designed to cycle nutrients (and energy) between piggeries, poultry and aquaculture and crops. A low capital input is claimed for Chinese biogas digesters, however it is acknowledged (van Buren, 1997) that this is achieved through the low labour cost in rural China. The actual construction and running costs need to be tested in a New Zealand context.

Biochar production, biogas production and gasification are potential technologies for reducing energy usage and carbon emissions in New Zealand apple production. Gasification may be preceded by sugar extraction and aerobic fermentation to produce ethanol. Of these, biogas production has advantages in that the technologies are well developed and readily transferable to a New Zealand setting, however it has disadvantages in requiring significant changes to existing practices.   Gasification requires less change to existing practices, and in fact supports production with traditional tree densities. Both biogas and gasification options require the development of a system for chipping and shredding wood and other plant material. Biogas also requires a composting step prior to anaerobic digestion. Biochar production returns less energy, but offers advantages in soil enhancement and carbon sequestration.

Chipping v mulching – A preliminary comparison of two cases.
An industry publication (McClintic, 2008) claims a consumption of 38 l of fuel in the production of 32 t of chipped wood from forestry waste (1.19 l/t), using a 473 kw chipping machine. This represents an energy ratio (output to input) of 184:1. No allowance is offered for the collection or feeding of the feedstock.

In comparison, an LCA study (Mila i Canals, 2003) reports a fuel consumption of 9 l hr^{-1} for a 60 hp orchard mulching mower. The process is described (from discussions with the managers of the orchards responding to the apple energy survey) as a mulching mower driven by a 90 hp tractor, mulching 4.5 m rows in two passes, performed as one central pass, followed by two sweeping passes with a "flicker", and a further central mulching pass. This description suggests the LCA report may underestimate consumption. In a 100 m square, 22 x 4.5 m row block, the distance travelled by the mulching tractor would be 6300m, and the flicking mower 4200 m.

Mulching mower	9 l hr^{-1}	@ 5kph	11.3 l ha^{-1}
Flicker	3 l hr^{-1}	@ 8kph	1.6 l ha^{-1}

Fuel consumption for current practice mulching operations is calculated as 2.6 l t^{-1} (Mila i Canals, 2003). The energy ratio is 85:1, (notwithstanding that the output is wasted). In current practice the energy used is accounted entirely as an energy input, whereas the chipping option, which appears to require a similar order of energy input, offers a significant energy return. Observation of mulching operations in practice reveals that the mulching blades wear rapidly, as proximity to the soil inevitably results in stones being picked up by the machine. A stationary chipping machine, fed by conveyor or hopper should be able to maintain sharper, more efficient cutting mechanisms. However, a machine that is able to process prunings *in situ* is preferred by growers.

Summary
Biomass residues from pruning operations in apple production may offer mechanisms for recovering energy and enhancing nutrition or soil fertility. Current mulching practices are argued to be relatively energy intensive and inefficient. Technologies developed for processing biomass should be investigated further as options for recovering solar-derived energy, and utilising it to replace fossil fuel inputs or enhance plant nutrition.

Appendix VI: Shipping analysis

Regression analysis

A regression analysis (Figure 6.1) was performed to predict energy usage from vessel power, gross tonnage and rated speed.

The estimates of energy usage were derived from fuel usage (itself derived from rated power), modified to incorporate other variables such as vessel payload and speed. An estimate of the energy use attributable to apples for a specific vessel was subsequently derived from three basic parameters: the rated engine power (kW), the gross tonnage (GT) and the rated cruising speed (kts). The total energy for refrigerated apples (MJ t^{-1} km^{-1}) was plotted as a function of rated power divided by gross tonnage and rated maximum cruising speed.
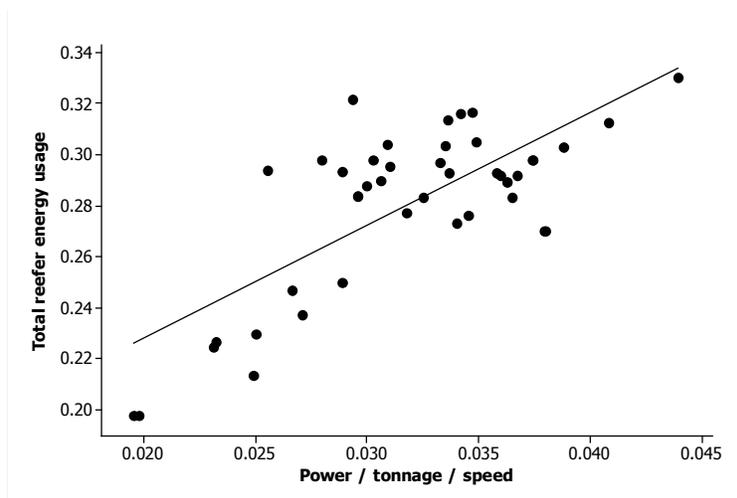
Figure 6.1 Predicting refrigerated apple freight energy use from vessel specifications.

The regression equation is:

total reefer energy usage (MJ t^{-1} km^{-1}) = 0.139 + 4.43 power GT^{-1} $speed^{-1}$ (p=0.000)

where:

- power is the rated power of the main engines measured in kW

- GT is gross tonnage

- speed is the maximum cruising speed measured in knots

Energy usage trends since the mid 1980's

A plot of vessel construction dates versus energy consumption reveals a trend toward reduction in energy consumption in vessels constructed since the mid 1980's (Figure 6.2). The advantage revealed in this analysis is however generated only by the basic relationship between the engine power, hull size and cruising speed as no specific account was taken of reported improvements in fuel efficiency (Buhaug et al 2009).
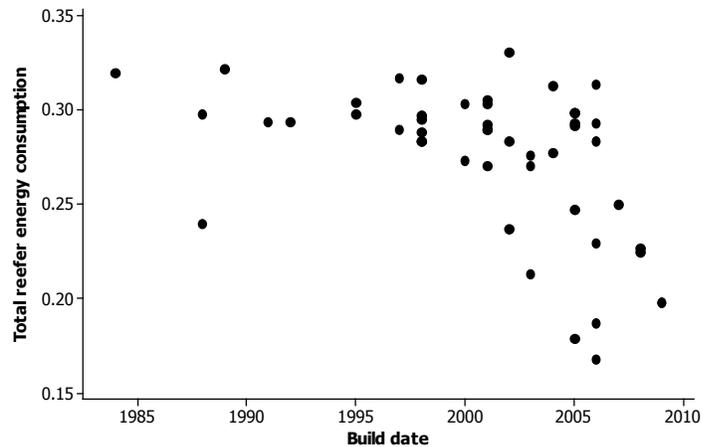
Figure 6.2 Improvement in shipping energy efficiency over time

The trend was driven by the increase in ship size and speed over time (Figure 6.3) in the sample group, which was influenced by a deliberate bias toward the new generation of container ships in the sample group (Sect. 3.5.2). If the actual fuel usage of the vessels were available it could be expected to show a more striking improvement in efficiency, as the relationship would be driven by the speed advantage of large hull size plus recent technological efficiencies (see Sect.2.2).
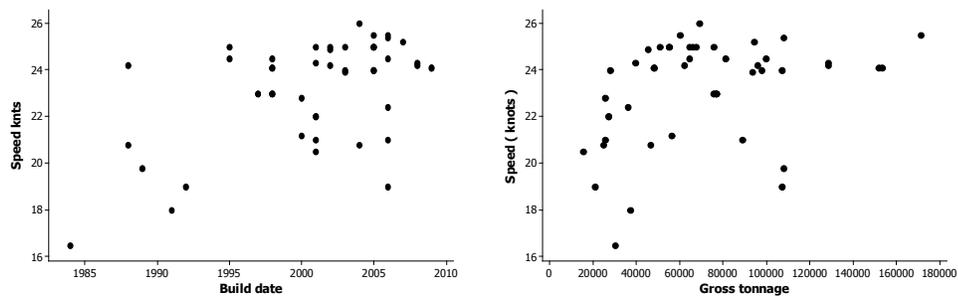
Figure 6.3 Relationships between vessel age, size and speed.
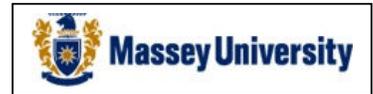
Appendix VII: Apple Production Energy Survey

Pipfruit NZ Inc is working with Massey University to learn more about energy usage in apple production. Initially we wish to benchmark energy usage. Ultimately we plan to address areas of high energy usage to identify ways of reducing production costs. The question we are asking is:

"How much energy goes into producing an apple?"

This question is becoming increasingly important to our customers. Knowing how much energy goes into producing a carton of pipfruit will help us become more efficient and plan for the future. This survey is the first step of a project that will measure energy inputs right to the supermarket shelf. The first step is to measure how much energy goes into producing fruit up to the orchard gate.

Pipfruit NZ is taking a positive approach to identifying areas where as an industry we can work better by working smarter. Please do your best to find answers for this survey, as the results may well help sell your fruit, and more significantly, help us identify the best current practices and develop new directions to ensure the long-term prosperity of our industry. The fact that we are a considerable distance from our major markets leaves us open to criticism from our competitors. We need to be able to show our customers that even though we transport our products significant distances, we are in fact efficient and responsible producers of fruit.

You will notice that we ask for your name and R-pin. To be of significant use to us, we need to be able to link the energy information to your specific orchard. If you are not happy about identifying your orchard, please supply whatever information you are able to anyway.

ALL records will be kept confidential to the study and no individual information will be released. Analysis will be on pooled information to identify specific areas of interest to the study and any published results will also be restricted to pooled information. Pipfruit NZ Inc. will be the arbiter of publication.

We are looking for results that cover a more or less complete season, roughly May 2003 to April 2004. You may find that our cut-off dates don't fit your records. Just tell us what you can.

This survey is part of a wider study. We are going to look at some orchards in greater detail. You will notice that one of the questions in this survey asks whether you would be prepared to be involved in a more detailed study. Please consider this carefully, as your participation in the full study will be of considerable value to the pipfruit industry.

If you any questions, please ring Greg Frater (a/h 06 856 6828) or Email G.Frater@massey.ac.nz

If you wish further comment contact Dr Mike Butcher, Technical Manager, Pipfruit NZ Inc. 021 406018 mike.butcher@pipfruitnz.co.nz

How much diesel, petrol and gas (LPG or CNG) did you use in the 2003-4 season?

One of the most easily measured items in the "energy budget" is the diesel and petrol used in vehicles and machinery. We would like to know how much fuel you consumed.

Monthly Fuel Use
Winter   1st May – 31st July 2003
diesel

                    petrol or gas

Spring/Summer   1st August – 31st January 2004

    diesel

petrol or gas

Harvest   1st Feb – 30th April 2004

diesel

petrol or gas

My answers to question one came from:

My records   **>**

An estimate   **>**

Total Electricity Consumption

Your electricity supplier has records of your orchard meter-box readings. It will save
us (and you) a lot of effort if we can request your records from your supplier.
However, we need your permission to do that.

I authorise Massey University to request my electricity records from my supplier.

R-pin   Account Name

Supplier

Name

Signed   Date

If you would prefer, you may supply this information from your own records. We don't want to know the cost of the electricity – we just want to know the amount of energy (number of electrical units) you used.

Winter 2003

Spring/Summer 2003-2004

Harvest 2004

Please tell us what you used electricity for. It is especially important for us to be able to exclude power use that isn't part of apple production up to the orchard gate.   (for example, power for post-harvest operations such as a cool-store.)

My electricity readings contain a significant component of:

Irrigation (and sprayfilling)   >

Frostfighting   >

Coolstorage   >

Packing   >

Other

Total Chemical Inputs

Agrichemicals already "contain" energy before they are even used. The energy inputs include the energy required to manufacture, package and distribute the chemical.

Some inputs may not be included in your IFP records. Urea is particularly important, as it is manufactured from natural gas, and has a very high "embodied energy" and is often applied in large quantities resulting in a significant overall increase to the energy inputs in production.

How much Urea did you use last year?

5. What are the characteristics of your Orchard ?

Region - be as precise as you can

Growing systems

Intensive (ha)   **>**

Conventional (ha)   **>**

Production system

Conventional   **>**

Organic   **>**

Transitional   **>**

How Much Fruit did you Produce this Season?

Total production (yield) per variety

_____

_____

_____

_____

_____

_____

_____

We need to look at a number of orchards in greater detail. If you have good records of energy usage, and think that you can provide more detail than this survey requires, we would like you to answer a more detailed survey in addition to this one.

I would be willing to answer a more detailed survey.   (tick)   **>**

Name: [   ]

Address: [   ]

Pipfruit New Zealand and Massey University thank you for your assistance. We look forward to working with you in the future.

Appendix VIII: The Contribution of Refrigerant Gases to GHG Emissions in Kiwifruit Production

-report to Landcare and MAF by G Frater, SEAT, Massey University

Key Findings

Refrigerant gas emissions varied from zero to 0.14 gms per tray (gross production). The industry mean (total gas used per gross production) was 0.043 gms TE^{-1}. Losses as a percentage of refrigerant charge ranged from zero to 25.7%. The total loss over the entire reported group calculated as a percentage loss against (partly estimated) total charge was 7.7%. Refrigerant losses were highly variable, and case specific[45].

Report contents

1.0 Methodology

2.0 Estimation of production volumes from reported coolstore area

3.0 Refrigerant emissions

4.0 Factors affecting refrigerant losses

5.0 Conclusions

6.0 Recommendations

1.0 Methodology

1.1 Data collection methods:

a. A survey (prepared by G. Frater and J. Mawson), distributed to selected Bay of Plenty coolstore/packhouse operations and export organisations

b. Personal visits, and subsequent telephone and email contact with the survey participants

c. A survey of Bay of Plenty refrigeration engineers

1.2 Responses

Useful data were reported by three post-harvest organisations and one refrigeration-engineering company representing a total of ten separate sites and 67 rooms. Two of

---

[45] TE is tray equivalent.

the post-harvest organisations operated from a single site, while one reported data
from two of three sites operated by the company.

In this report, emissions were reported against gross production (exported fruit plus
local market), which totalled 21.4 m tray equivalents (TE) for the surveyed group (an
estimated 24% of the NZ crop).

Other production indicators were:

Packout (export production/fruit received)   85%

Gross production/fruit received   88%   (12% to fodder or waste)

Export production /gross production   97%   (3% local market)

Three coolstores reported the sale of waste fruit as fodder, while none was reported as
buried on site or as landfill.

Fig 8.1 shows the static capacity of the 10 coolstores. Stores 1-4 were large operators
with 12-19 rooms. Stores 5-10 were smaller operators with single room stores.
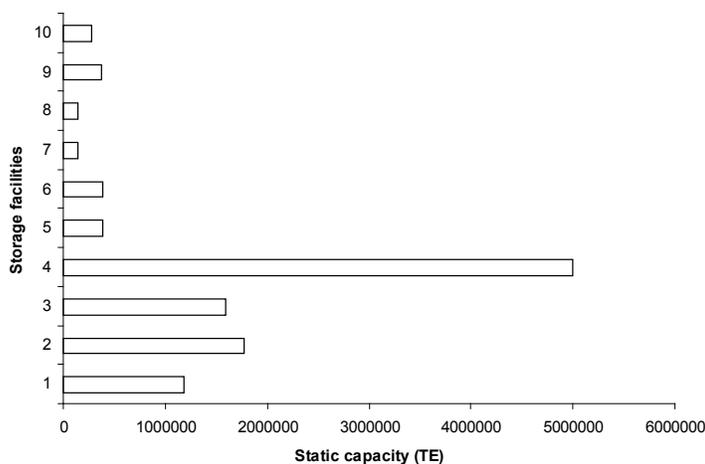
Figure 8.1 Static capacity of coolstores

2.0 Estimation of production volumes from reported coolstore area

Data reported by a refrigeration engineer related to six separate sites, and was
reported as gas losses against coolstore area. Incorporating this data in the final
reported emissions is critical to achieving a reasonably broad sample group. The

following method was developed to extrapolate the reported coolstore area into kiwifruit production volumes.

2.1. Deriving static capacity from reported area

Firstly the static capacity of the coolstores reported by the refrigeration engineer was derived from values reported by coolstores 1-4 (summarised below). The production attributable to those coolstores was then derived from the relationship between static capacity and production (reported by coolstores1-4).

Coolstore 1 reported the area of a single representative room (1 of 12). The value derived for storage capacity to area was 114 TE m^{-2}. This value was regarded as the least reliable of the reported values, and was disregarded in favour of the more detailed information provided by coolstores 3 and 4. (The calculation of static capacity is a simple calculation based on the number of pallets that can be stored, two layers high, on a given floor area. The consistent value reported by coolstores 3 and 4, and checked against the physical plans provided by coolstore 4 is regarded as reliable. The value provided by coolstore 1 may be an error or miscalculation by the data provider.)

Coolstore 2 reported the static capacity of 15 rooms, and the mode of usage (conventional or controlled atmosphere (CA)), but not the physical area.

Coolstore 3 reported the dimensions of 15 rooms. The equivalent static capacity was also reported for each room, plus the mode of usage. The mean values derived were 465 TE m^{-2} for CA rooms, and 309 TE m^{-2} for conventional rooms. These values were double-checked by management staff from the coolstore. A second set of calculations based on pallet capacity were prepared for the CA rooms, but since they normally store bins, the tray equivalent value of the bin capacity was preferred.

Coolstore 4 provided full plans for a single representative room. This store provided the capacity and the layout (conventional pallet storage) for this room. A value of 309 TE m^{-2} was calculated from the figures provided (corresponding exactly with coolstore 3 above).

2.1.1 Coolstore static capacity variables

While coolstore layout design impacted on the static capacity, the main variable was mode of usage. Fruit stored in CA is stored in bins, and while conventional storage can be in bins or pallets, the static capacity of these conventional stores was invariably reported as pallet capacity. Coolstore 3 has a wall height of 5m, while the larger capacity rooms of Coolstore 2 have a height of 7m. Some coolstores report rack systems that allow palletised fruit to be stored three pallets high, increasing the capacity by 33%. Normal pallet storage height was reported as two layers of pallets.

The stores reported by the refrigeration engineer were all conventional stores, so the mean capacity reported by stores 3 and 4 ($309TE/m^2$) can be applied to derive static capacity. The occasional storage of binned fruit in these stores would result in a higher static capacity, and a slightly more conservative emissions value.

2.2 Estimating production volume from static capacity

The three post-harvest organisations (four coolstores) reported production figures and static capacity. The ratio of gross production to static capacity reported ranged from 1.54:1 to 2.78:1 with a mean of 2.07:1. The mean ratio (2.07:1) was selected as an appropriate value for estimating production volumes for the six additional coolstores reported by refrigeration engineers. (The figures provided by these four large operations show that for the 2007 season the total kiwifruit production was approximately double the volume of fruit that can be stored at any one time. This relationship was used to derive a production value for the six small stores who reported refrigerant loss against coolstore area. The refrigeration engineer who reported this data was able to accurately report coolstore area, but did not have access to production output data.)

3.0 Refrigerant emissions

Refrigerant gas replaced in maintenance and servicing was regarded as a GHG emission. Refrigerant gases reported as used in new installations were excluded from this report.

3.1 Gasses deployed in kiwifruit coolstores

The gasses reported as being used in the surveyed coolstores were:R22, R404A and R134A.

3.2 Usage (emissions)

Usage varied from zero to 0.14gms per tray (gross production).

The industry mean (total gas used / gross production) was 0.043gms/TE.

The totals reported were:

R22, 427 kg; R404, 473kg; R134A 25kg.

3.2.1 Losses per Gross TE
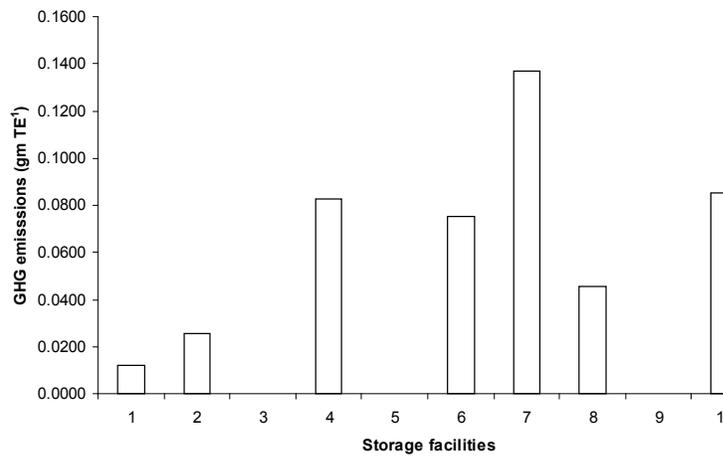
Figure 8.2 Refrigerant loss per tray equivalent

Figure 8.2 shows the losses per gross TE (export plus local market production) for the 10 cases reported. Case three was 0.00011gms/TE, while cases 5 and 9 have zero recorded losses. Case four was responsible for 68.7% of the total emissions of the xx [SM1] the entire group of ten stores (this case also has the highest production of the sample group). See 4.0 for further discussion.

3.2.2 Losses as a percentage of charge

The total loss over the entire reported group calculated as a percentage loss against (partly estimated) total charge was 7.7%. Only two coolstores (totalling 27 rooms) reported the total charge of refrigerant gases:

- Coolstore 1 reported their total refrigerant charge (R134A, 150kg; R22, 400kg; R404A, 700kg). The losses of 25kg represent 2% of the total charge. The plant design consists of both central and separate refrigeration systems.

- Coolstore 2 reported their total charge (R22, 600kg: R404A, 1100kg). The losses (100kg) represent 5.9% of the charge. The plant design consists of both central and separate refrigeration systems.

- Coolstore 3 did not report their total refrigerant charge. This operation has a similar layout (15 rooms, capacity 160,000 TE) to coolstore 2. If the same total charge (1700kg) is assumed, the losses (0.5kg) represent 0.03% of the charge. This operator reports that they experience very low losses – their last significant loss being 40.2kg due to a leak in 2006

- Coolstore 4 reported refrigerant losses for the period April 2007 – May 2008. (The survey requested results for the calendar year 2007). This store did not report its total charge, so it was estimated on the basis of the ratio of charge to static capacity for coolstores 1 and 2 (0.0011kg per TE). Their losses (635.1kg) represent 11.5% of the estimated total charge. These losses (0.08gms/TE) were the highest of those reported by the four large operators. Coolstore 4 commented that the year April 2007 – May 2008 was particularly bad for refrigerant loss, and that they have not replaced any further refrigerant (from May 2008 to November 2008). The last month reported incurred losses of 327kg, and impacted on the final indicator value reported.

Coolstores 5-10 (reported by refrigeration engineer) were allocated a total charge on the basis of the mean of stores A and B per TE static capacity. On this basis their losses vary from zero to 25.7% and were generally higher and more variable than the large operators. Figure 8.3 shows loss as a percentage of charge for each store. Note the higher losses and variability of cases 5-10.
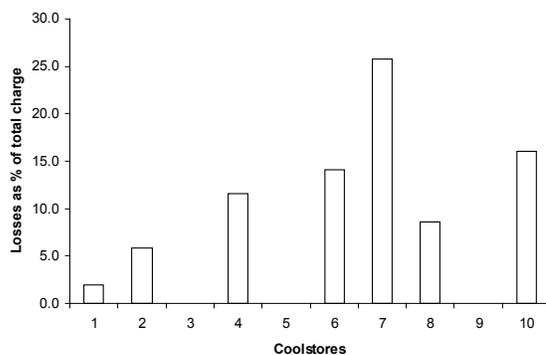
Figure 8.3 Refrigerant losses as a percentage of charge

4.0 Factors affecting refrigerant losses

The following discussion was based on personal interviews with, and written feedback from senior managers in post-harvest operations, plus interviews and written feedback from refrigeration engineering companies. The factors affecting refrigeration losses include:

- Plant design (eg bad bracketing)
- metal fatigue
- vibration
- bad joins (i.e. poor or hurried construction)
- forklift operator training
- collisions with plant and pipework
- failure to recognise damage or potential failures
- insufficient maintenance
- plant age.
- mode of usage. (CA stores are "locked down" resulting in reduced opportunity for forklift damage)

One senior manager commented that in his opinion the most significant losses of refrigerant gas occur during catastrophic events such as fires or forklift damage. That is, events that involve total replacement of the gas charge are more significant than small leaks (surreptitious losses). This comment was only partly supported by the evidence. Coolstore 4 reported losses averaging 43.8kg a month. However in one month, replacement of 327kg occurred. Personal communication with the engineer confirmed that this replacement was genuine replacement (not a new installation), and it was assumed to have been caused by catastrophic loss due to damage or major malfunction. Such losses could be through unique events, or alternatively could be systemic, resulting from a plant design or operational factor repeated throughout an organisation's installations.

While coolstore 4 lost an average 43.8 kg a month, coolstore 3 lost just 0.04 kg per month, and considered a single loss of 40 kg two years ago to be a significant loss. This variation reinforces the likelihood of systemic issues either in plant design or operator practice as being likely causes of the losses. In the case of coolstore 4,

catastrophic losses would exceed surreptitious losses by several hundred percent. The only observable difference between coolstore 4 and the other three larger operators (1, 2 and 3) was that coolstore D did not have CA facilities where the other three operators do. It was noted above that the mode of usage may impact on losses.

Figure 8.4 shows the monthly losses for store 4. In month 12 the losses consisted of three units of 109 kg (ten 10.9 jugs of refrigerant). It appears that the losses were due to five separate major events, and two lesser events. While some of the losses were possibly explainable as surreptitious losses, the event-based explanation appears more likely.
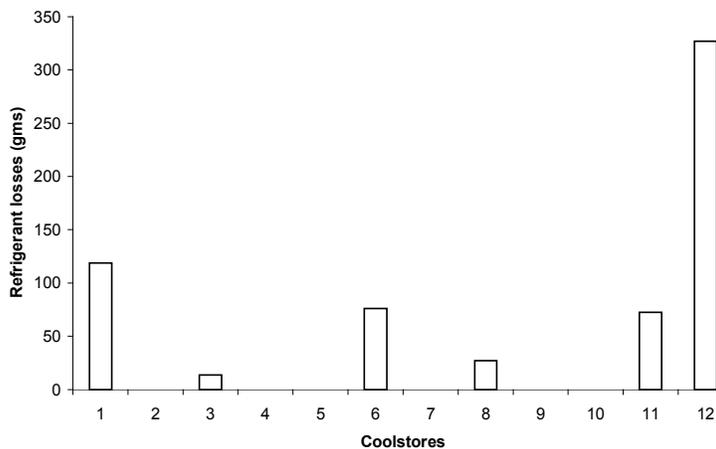
Figure 8.4 Refrigerant losses (gms) per month for store 4

Coolstores 5 to 10 were all conventional stores, and were equivalent in size to single rooms operated by the four large operators. The variation within these stores can be understood in terms of all the factors listed above as they apply to smaller operators.

Conclusions

Refrigerant losses from coolstores as represented in the sampled group were highly case specific. Even though the crop throughput for the sampled group represents 24% of the national crop, the variation within the sampled group was sensitive to single events (specifically catastrophic losses from individual large plants).

Appendix IX: Post Harvest Survey

Institute of Technology and Engineering
Massey University
Private Bag 11 222

Researcher   Greg Frater

Supervisors   Professor Ralph Sims

                 Associate Professor John Mawson

Introduction

A key objective of this research is to establish reliable data for energy inputs into New Zealand apple production. The orchard component of this research was completed in 2006. We are now looking to measure energy inputs for the remainder of the value stream - from orchard gate to market. Previous research has been based on process values published in early literature. The intention for this research is to measure actual values from representative operations.

The data we require will be reported in the form of energy inputs (e.g. megajoules) per kg of product. As far as possible, we need to tie the energy inputs to a discrete volume of crop.   This will be best achieved by reporting data from three recent seasons (the orchard data was 2003-2004).

The specific information we require is three season's production figures as well as electricity (and fuel) usage figures for your packhouse(s) and coolstore(s). The study is limited to energy inputs and so will be analysed as kilowatt/hrs and reported as megajoules or gigajoules not dollar values.

If you have these records or in some other form that would be easier for you to submit (eg per variety), please submit them in that form, or contact the researcher and request him to change the form.

Records representing a single packhouse should be sufficient, but if you think it would be better to submit records for more than one packhouse, please photocopy the appropriate tables.   However, we are requesting that you submit data from as many coolstorage facilities as you are able.

If you would prefer the researcher to work through this questionnaire with you, please contact Greg Frater.

Questionnaire:

If your data relates to a season other than a Jan 1 to Dec 30 calendar year (eg September to September) please note this here or alongside the tables.

_____

_____

Packhouse Production

	2007	2006	20___
Gross Production (kg)			
Export Production (kg)			
Average Packout %			

Percentage of Company Crop Handled by this Packhouse			

Packhouse electrical meter readings: Note – a requirement for our research is to separate refrigeration energy from packing process.   Please identify any demand on these meters that has a refrigeration component, or components outside of typical grading/packing process (eg workshop).

	2007	2006	20___	% refrigeration or other
Meter 1				
Meter 2				
Meter 3				

Do you have an on-site engineering workshop, or any other significant power demand other than those related to packing/grading or staff needs.

No_____

_____

If yes, does your workshop do significant work for outside customers (including your own orchards)?

_____

_____

_____

Seasonal Production
Please report your export production by packaging type (there are differences in energy inputs between different packaging types).

Production kg	2007	2006	20____
Total cartons			
Total export bin-type			
Total RDT or tray type			
Other packaging types			

How much fruit went to local markets and process?

	2007	2006	20____
Process			

Local Market			

Please record fuel used in your packhouse operations by forklifts or general vehicles (not trucks). You may prefer to record hours or kilometers

LPG /CNG			
Petrol			
Diesel			

Coolstore Energy
Please list the coolstores within your operation, and describe their use, age and technology (eg CA, short term conventional coolstore etc).

Coolstores

	Site / Address	Year Coolstore Constructed	Description
A			
B			
C			
D			

The objective in the following section is to assign a value for seasonal power usage to your export crop. We need to link the coolstore energy figures to the packhouse production figures you reported. The ideal case would be if all the fruit that you processed in your packhouse(s) passed through one or more coolstores, and that coolstore did not handle any other produce. Any variation from this will need to be reported. Please identify any difference between the volume of export fruit accounted in your packing figures and the volume that passed through your coolstores.

This data can be quite general if necessary. For example, you could report that 10% of the export volume packed in a particular season was contracted to another company's coolstores. You may find it more straightforward to report the fruit volumes that passed through a particular coolstore by date and volume on a separate spreadsheet.   If one or more coolstores is used for post-harvest chilling (prior to packing) please note here.

Coolstore ID	Coolstore throughput as a %age of packed fruit, or absolute volume of fruit that passed through each coolstore.

Please record the seasonal electricity usage for each coolstore.

Electricity Usage	Meter ID	Yr **2007**	Yr **2006**	Yr 20___
Coolstore ID A				
Coolstore ID B				
Coolstore ID				
Coolstore ID				

Please record your fuel usage for your coolstore operations. If these are already reported above in your packhouse figures, leave the cell blank.

Fuel Usage		Yr 2007	Yr 2006	Yr 20___
Coolstore ID	gas			
	petrol			
Coolstore ID	gas			
	petrol			
Coolstore ID	gas			
	petrol			
Coolstore ID	gas			
	petrol			

Distances/volumes
I need to know how far fruit travels in order to get to your packhouse(s).
You can provide the name and address of the orchards that supply your packhouses, or alternatively, to retain the confidentiality of the orchards you can estimate the distance of each orchard from your packhouse and the volume of fruit they supplied per season.

Orchard ID	Yr	Fruit Volume	Distance from packhouse	Physical Address

Where does your fruit go? I need to know the volumes of fruit that are despatched to specific overseas ports. If you only know the market, but not the port, please provide that information. These figures can be in export tonnage or in percentage of total crop. I will assume that all your crop is exported from Nelson Port.

Fruit Volume per yr. TCE / List Ports	Yr **2007**	Yr **2006**	Yr 20___

How long does your fruit stay in your coolstores? You may have to help me with the best approach to this question. I assume that your conventional coolstores receive a steady stream of fruit throughout the season, but that fruit that goes into CA is assembled over a shorter time period. I also assume that export fruit leaves your coolstores in large shipments, and that local market produce leaves your coolstores in smaller more frequent shipments.

Would it be reasonable to build a simple model based on a steady flow from your packing facilities from the start to the end of the season, plus outgoings based on shipping dates and volumes?

_____

_____

_____

_____

If so please provide the dates and volumes for shipping, and the opening and finishing dates for each coolstore.
Shipping Dates

Yr1		Yr2		Yr3	
Date	Tonnage	Date	Tonnage	Date	Tonnage

Coolstore Start and Finish Dates (First crop received to last shipment)

Coolstore ID	Year 1 2007		Year 2 2006		Year 3	

Thank you for your assistance with this project. If you can see any significant omissions, or flaws in this methodology, please discuss it with us.

Greg Frater

Appendices X and XI

See CD ROM for:

Appendix X   MS Excel spreadsheets

Appendix XI   pdf file

Appendix XII: Strategic Assumption Surfacing and Testing (SAST)– an adaptation of a management method to the sustainability context

The SAST method (Mason and Mitroff, 1981) was developed for surfacing assumptions in the strategic planning arena. The framework of this method lends itself to testing assumptions in the sustainability field. This adoption of a social science method derived from soft systems thinking is consistent with the nature of sustainability issues. The underlying purpose of sustainability research is to better understand local and global environments so that human decisions don't impact negatively on future populations. These are essentially strategic planning issues, so the context of the method is consistent with the intentions of the method as it stands.

The SAST methodology is typically applied to a proposed strategy, whereas in this new application of the method, the testing of assumptions is required before new strategies can be formulated. Applying SAST to interventions in global food supplies is strategic in nature, and in this respect, fits the intent of the SAST methodology.

The SAST method is a participative group method that follows five phases:

Group formation: The original method suggests multiple groups (of 6-8 persons). The method looks for differing perspectives between groups, but advises against conflicting attitudes or points of view within a group. In an investigation of scientific assumptions, it is assumed that all the participants are familiar with the field in question. If the integrity of the method is to be retained, and the strategies in question are regarded as critical, then multiple groups should be formed, possibly in different venues linked by a technological solution.

Assumption surfacing and rating: The SAST methodology requires the assumptions to be assigned to stakeholders. In organisational assumption testing, a group typically begins by identifying stakeholders. In this case, it is the assumptions of researchers, reviewers and publishers that are being surfaced and tested. Normally it would be assumed that research is independent of the socio-political context of these stakeholders, however it is precisely this assumption that is being challenged in the

present research. In the arena of sustainability research, there are differences; sometimes subtle, sometimes overt in the frames of reference of researchers from highly industrialised European contexts, and researchers from developing or even just geographically isolated contexts.

Dialectic debate: The group debates within itself whether or not an assumption is relevant. The designers of the method suggest a "devils advocate" technique of proposing the converse state of an assumption. In the arena of assumption testing for sustainability research, when assumptions are being tested prior to the development of strategies, it is the context of likely applications of an indicator that must be considered. (For example: "if the converse of an assumption is true, would it affect the application of an indicator in the climate change debate?"). If the opposite is true, and it doesn't affect a mooted application, then the assumption can be disregarded. Assumptions that survive this culling process are ranked by entering them on a 2 x 2 matrix (Fig. 11.1). One axis measures the impact of the assumption (the extent to which an incorrect assumption would impact on the proposed action), while the other axis measures plausibility (confidence in the correctness of the assumption).

Dialectic debate between groups: In this sustainability application, the debate would focus on assumptions that plot in the "high impact, low certainty" sector of the grid. In the arena of sustainability research, these are the assumptions of low certainty that if incorrect will seriously undermine the safety of new knowledge and the efficacy of interventions based on this knowledge.

Final Synthesis: The SAST methodology prescribes actions at this stage that are directed towards proceeding with appropriate organisational strategies. In the sustainability arena, the identification of assumptions in the critical sector of the matrix requires close examination of the components (data, logical arguments) of the indicators. It may be that agreement can be reached, and that a new, safer indicator can be derived from the original data.

The adaptation of the existing method is proposed to facilitate the surfacing and testing of assumptions underlying sustainability indicators. The purpose is to avoid the unintentional application of indicators containing hidden assumptions that are inconsistent with the context in which they will be applied (Sect. 4.2.3)

A significant challenge in applying this method lies in the step of articulating scientific assumptions (step 2 above). To achieve this, it is useful to describe the context in which the research in question was conducted, and the context in which it will potentially be applied. Examination of a context allows the immediate construction of a primary level of assumptions relating to the historical development of that context. For example, if we examine energy indicators published in the early 1980s, we can ask questions such as:

What were the issues that prompted this research?
Answer
The oil crisis of the mid 1970s
Increased awareness of the reliance of food production systems on fossil fuels

What sector was the science intended to inform?
Answer
National and international agencies and industries undertaking strategic planning for food production
Agencies and industries undertaking strategic planning for energy supply

The researcher may well identify other issues, and other sectors of application, but the issues and sectors listed serve to illustrate the method. The word "issues" has proven very powerful in other soft system methods (Brassard, 1996), promoting an open ended exploration of factors influencing research at a particular time. Fortunately scientific reports are typically diligent in recording precise answers to these questions. Similarly, by questioning whom the research was intended for, we are simply placing ourselves in the mindset of the researchers of that era.

The next step is the examination of the context of current research:

What are the issues that are prompting current research?
Answer
All the issues above, described as being the context of the earlier research, plus:
The emergence of global warming and climate change research, including the significance of greenhouse gases and the acceleration of environmental degradation

What sector is the science intended to inform?

Answer

All the agencies listed above, plus a wider range of agencies at higher levels of national and international strategic planning

Having identified the two contexts, it is now possible to articulate a basic assumption, and subsidiary assumptions.

Basic assumptions

Assumption a. That the values derived in the context of the issues surrounding the earlier research are valid in the context of a new and wider range of issues.

Assumption b. That the values derived to inform the sectors for which the earlier research was conducted are valid to inform policy-making functions at the higher levels.

Subsidiary assumptions

Assumption c. Indicators derived in the context of energy supply issues are valid in the context of climate change and global warming.

Assumption d. Indicators derived in the context of energy supply issues are valid in the context of accelerating environmental degradation

Assumption e. Indicators derived to inform food supply and energy supply agencies are valid to inform high level strategic planning agencies.

These basic assumptions can now be articulated in terms of the relevant stakeholders:

Assumption a1. That European researchers, reviewers and publishers would consider the context of issues surrounding the earlier research to be valid in the context of a new and wider range of issues.

Assumption a2. That developing country researchers would consider the context of issues surrounding….

Assumption a3. That Australasian researchers would consider…

These assumptions combine groups of stakeholders, and groups of issues. Even so, a minimum of fifteen assumptions is represented in this condensed treatment. It is the task of the research group to reach consensus on which factors can be aggregated, and which must be further dissected.

In the assumption testing matrix below, the most critical assumptions are those for which the validity is uncertain, and the impact of an incorrect assumption is high. There are likely to be a number of assumptions in the high impact/certain validity, and the low impact /uncertain validity zones, but the process should be trusted to the extent that these assumptions can be regarded as safe.
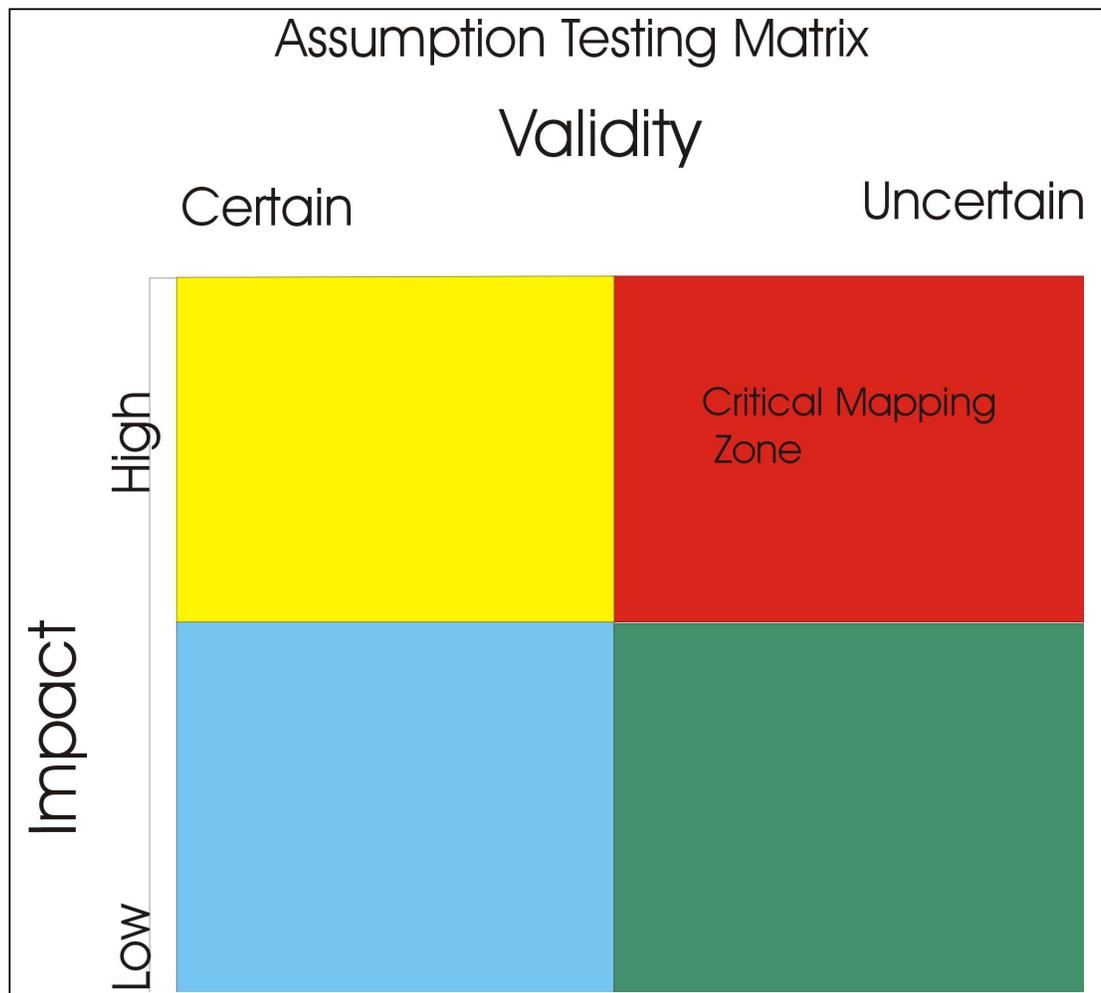

Fig 11.1 SAST assumption testing matrix

Glossary

Terms:

agrichemical	insecticides, fungicides, herbicides and control substances (including those approved for OFP production)
capital inputs	farm level plant, machinery, buildings and structures (excluding land and trees)
hydraladder	hydraulically operated motorised picking platform (trade name Hydraladda)
lift-truck	forklift
normative	of, or pertaining to norms or standards (i.e. states of goodness or badness)
normativistic	arguments based on the assumption that normative truth is valid and meaningful
packhouse	fruit industry term for packing shed
PipSure	programme replacing former IFP programme
PipSafe	ultra low residue pipfruit production programme
positivism	human thought based on the belief that "positive truth" can be achieved by experimental and objective observation
positivistic	arguments based on as assumption of positivism
reefer	refrigerated hold ship, or refrigerated container

Abbreviations:

CAN	Calcium ammonium nitrate
CLD	Causal loop diagrams
CNG	Compressed natural gas
CSH	Critical system(s) heuristics
DEFRA	Department for environment, food and rural affairs (UK)
DWT	Deadweight tonnage (marine)
EPA	Environmental Protection Agency (US)
FAO	United Nations Food and Agriculture organisation
FEU	Forty foot equivalent (shipping container)

GHG	Greenhouse gas
GT	Gross tonnage (marine)
HGV	Heavy goods vehicle
LCA	Life cycle analysis
LCI	Life cycle inventory
LCM	Life cycle management
LCT	Life cycle thinking
LOA	Length overall (marine)
LPG	Liquefied petroleum gas
MAF	Ministry of Agriculture and Forestry (NZ)
MRI	Marine research institute
IMO	International maritime organisation
IFP	Integrated fruit production
IPCC	Intergovernmental panel on climate change
OFP	Organic fruit production
PTO	Power take-off
TCE	Tray carton equivalent (for apples, 18.5 kg)
TEU	Twenty foot equivalent (shipping container)
TLCI	Total life cycle intervention
TNS	The Natural Step
TSI	Total systems intervention
RSI	Unit of insulation
SAST	Strategic assumptions surfacing and testing
SD	System dynamics
TE	Tray equivalent
VSM	Viable system model

References

Amthor, J. (1991) Respiration in a Future, Higher-[CO_2] World. *Plant, Cell and Environment* 14**,** 13-20.

Anon (1994**)** *Food Miles Report*. London, SAFE Alliance.

Apaiah, R.K., Linnemann, A.R., van de Kooi, H. J. Exergy Analysis: A Tool to Study the Sustainability of Food Supply Chains. (2006) *Food Research International* 39, 1-11.

Apelbaum, C. G. (2003) *Australian Maritime Transport*. Australian Shipowner's Association.

Arrous, J. (2000) Energy Input-Output Economics: What's the Matter? *13th International Conference on Input-Output Techniques*. Macerata, Italy.

Ashby, W. R. (1952) *Design for a Brain: The Origin of Adaptive Behaviour,* New York, Wiley.

Audsley, E., Alber, S., Clift, R., Cowell, S. J., Crettaz, P., Gaillard, G., Hausheer, J., Jolliett, O., Kleijn, R., Mortensen, B., Pearse, D., Roger, E., Teulon, H., Weidema, B. & Van Zeijts, H. (1997) *Harmonisation of Environmental Life Cycle Assessment for Agriculture,* Brussels, European Commission DG VI Agriculture.

Austin, P. T. & Hall, A. J. (2001) *Temperature Impacts on Development of Apple Fruits*. In Warrick, R. A., Kenny, G. J. & Harman, J. J. (Eds.) The Effects of Climate Change and Variation in New Zealand: An Assessment Using the Climpacts System. Hamilton, University of Waikato.

Barber, A. (2004a) Seven Case Study Farms: Total Energy & Carbon Indicators for New Zealand Arable & Outdoor Vegetable Production. *AgriLINK New Zealand Ltd.*

Barber, A. (2004b) Total Energy and Carbon Indicators for New Zealand Kiwifruit Orchards: A Pilot Study. *AgriLINK New Zealand Ltd.*

Barber, A. (2009) NZ Fuel and Electricity - Total Energy Use, Carbon Dioxide and GHG Emission Factors. *AgriLINK New Zealand Ltd.*

Barber, A. & Pellow, G. (2005) Energy Use and Efficiency Measures for the New Zealand Dairy Farming Industry, *AgriLINK New Zealand Ltd.*

Batchelor, T. A., Walker, J. T. S., Manktelow, D. W. L., Park, N. M. & Johnson, S. R. (1997) New Zealand Integrated Fruit Production - Charting a New Course. *50th N.Z. Plant Protection Conference*.

Bazari, Z. & Reynolds, G. (2005) Sustainable Energy in Marine Transportation. Sustainable Shipping, *Lloyd's Register EMEA, IMarEST Conference*.

Beck, E.-G. (2007) 180 Years of Atmospheric CO_2 Gas Analysis by Chemical Methods. *Energy and Environment,* 18**,** 259-282.

Beckford, J. (1998) *Quality,* London, Routledge.

Beer, S. (1979) *The Heart of the Enterprise,* New York, Wiley.

Beer, S. (1981) *Brain of the Firm,* Chichester, John Wiley and Sons.

Beer, S. (1984) The Viable System Model: Its Provenance, Development, Methodology and Pathology. *Journal of the Operational Research Society*, 35**,** 7-25.

Blanke, M. M. & Burdick, B. (2005) Food (Miles) for Thought: Energy Balance for Locally-Grown Versus Imported Apple Fruit. *Environmental Science and Pollution Research*, 12.

Bohm, D. (1980) *Wholeness and the Implicate Order*, London, Routledge.

Boustead, I. & Hancock, G. F. (1981) *Energy and Packaging Systems from Energy Materials: Requirements of Beverage Containers and Packaging Systems,* New York, Halstead Press.

Boxelaar, L., Paine, M., Shaw, H. & Linehan, C. (2003) Solutions for the Environment - but What Are the Problems? An Exploration of Approaches to Deal with Issues of the Environment. *Solutions for a better environment: 11th Australian Agronomy Conference.* Geelong, Victoria, Australia.

Bras-Klapwijk (1998). Are Life Cycle Assessments a Threat to Sound Public Policy Making? *International Journal of Life Cycle Assessment.* 3 (6) 333-342

Brassard, M. (1996) *The Memory Jogger Plus+,* Salem, Goal/QPC.

Bridgewater, A. V., Meier, D. & Radlein, D. (1999) An Overview of Fast Pyrolysis of Biomass. *Organic Geochemistry,* 30**,** 1479-1493.

Browne, M., Rizet, C., Leonardi, J. & Allen, J. (2008) Analysing the Energy Use in Supply Chains: The Case of Fruits Vegetables and Furniture. *Proceedings of the Logistics Research Network Conference,* Liverpool.

Brundtland, G. H. (1987) *Our Common Future / World Commission on Environment and Development,* Oxford; New York, Oxford University Press.

Buhaug, Ø., Corbett, J. J., Eyring, V., Endresen, Ø., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A. Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Wanquing, W., Winebrake, J. J. & Yoshida., K. (2009) *Second IMO GHG Study,* London, UK., International Maritime Organization (IMO).

Carlsson, A. (1997) *Greenhouse Gas Emissions in the Life-Cycle of*

Carrots and Tomatoes. Department of Environment and Energy
Systems Studies, Lund University, Sweden. IMES/EESS Report No. 24

Carson, R. (1963) *Silent Spring,* London, Hamish Hamilton.

Chao, L., Peiyuan, J., Naxin, W. & Yiliang, C. (1995) Energy Save in
Ship's Refrigeration and Air Conditioning System with VVVF. *The
5th International Symposium on Marine Engineering.* Yokohama.

Checkland, P. (1985) From Optimising to Learning: A Development of
Systems Thinking for the 1990's. *Journal of Operations Research
Society,* 36**,** 757-767.

Checkland, P. (1999) *Systems Thinking, Systems Practice*, New York,
John Wiley and Sons, Ltd.

Checkland, P. (2000) Soft Systems Methodology: A Thirty Year
Retrospective. *Systems Research and Behavioral Science,* 17**,** 11-58.

Checkland, P. & Scholes, J. (1990) *Soft Systems Methodology in Action*,
Chichester, John Wiley and Sons.

Chow, J., Kopp, R. J. & Portney, P. R. (2003) Energy Resources and
Global Development. *Science,* 302**,** 1528-1531.

Churchman, C. W. (1972) Perspectives of the Systems Approach.
Interfaces, 4.

Churchman, C. W. (1979) *The Systems Approach and Its Enemies*, New
York, Basic Books Inc.

Clark, H. (2002) Ruminant Methane Emission Measurements and Estimates - from
Gut to Globe. *Proceedings of the New Zealand Society of Animal Production,* 62.

Cleland, D. J. (2005) Sustainable Energy Use and Management, in People and Energy: How Do We Use It? *Royal Society of New Zealand Conference*. Christchurch, The Royal Society of New Zealand, Miscellaneous Series.

Condron, L. M., Cameron, K. C., Di, H. J., Clough, T. J., E.A.Forbes, Mclaren, R. G. & Silva, R. G. (2000) A Comparison of Soil and Environmental Quality under Organic and Conventional Farming Systems in New Zealand. *New Zealand Journal of Agricultural Research,* 43**,** 433-466.

Corbett, J. J. & Koehler, H. W. (2003) Updated Emissions from Ocean Shipping. *Journal Of Geophysical Research*, 108.

Cowell, S. J. (1998) *Environmental Life Cycle Assessment of Agricultural Systems:Integration into Decision-Making*. Centre for Environmental Strategy. Guildford (UK), University of Surrey.

Cruz, L. M. G. (2002) Energy-Environment-Economy Interactions: An Input-Output Approach Applied to the Portuguese Case. *7th Biennial Conference of the International Society for Ecological Economics Environment and Development: Globalisation & the Challenges for Local & International Governance*. Sousse (Tunisia).

Cubasch, U., Hasselmann, K., Hock, H., Mair-Reimer, E., Mikolajewicz, U., Sausen, R. & Santer, B. (1992) Time-Dependent Greenhouse Warming Computations with a Coupled Ocean-Atmosphere Model. *Climate Dynamics*, 8 55-69.

Curran, M. A. (1993) Broad-Based Environmental Life Cycle Assessment. *Environmental Science Technology*, 27.

Dalzell, J. (1999) *Food Industry and the Environment in the European Union - Practical Issues and Cost Implications*, Springer.

Delft, C. E. (2006) *Greenhouse Gas Emissions for Shipping and Implementation Guidance for the Marine Fuel Sulphur Directive*. Germanischer Lloyd, Marintek Det Norske Veritas.

de Sa, J. (2007) *School-Based Fruit and Vegetable Schemes: A Review of the Evidence.* London, London School of Hygiene and Tropical Medicine.

Dravid, D., Brown, L.J. *Heretaunga Plains Groundwater Study*. Hawke's Bay Regional Council. Napier.

East, A. R., Love, R. J., Mclaren, R. G. & Hume, A. S. (2009) Product Allocation of Greenhouse Gases Produced by Coolstorage Facilities. *Energy Post Graduate Conference.* Massey University, Palmerston Nth, NZ.

EECA (2007) *Forest Residue Harvesting for Bioenergy Fuels*. Energy Efficiency and Conservation Authority.

Elghali, L., Cowell, S.J., Begg, K.G., Clift, R. (2006) Support for Sustainable Development Policy Decisions. A Case Study from Highway Maintenance. *International Journal for Life Cycle Assessment*. 11, Special issue 1, 29-39.

Elgowainy, A., Gaines, L. & Wong, M. (2009) Fuel-Cycle Analysis of Early Market Applications of Fuel Cells: Forklift Propulsion Systems and Distributed Power Generation. *International Journal of Hydrogen Energy*, 34**,** 3557-3570.

Elliot, S. L. & Mumford, J. D. (2002) Organic, Integrated and Conventional Apple Production: Why Not Consider the Middle Ground? *Crop Protection,* 21**,** 427-429.

Engstrum, K., Eriksson, K.-E., Hubendick, B., Robèrt, K.-H., Tiberg, N., Wallgren, B. & Wijkman, A. (1990) Energy Issues from a Scientific Perspective. Energy Consensus Paper. *Det Naturliga Steget*

EPA (2000) *Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data*. Office of Transportation and Air Quality U.S. Environmental Protection Agency.

FAO (2006) *The Right to Food Guidelines - Information Papers and Case Studies*. Publishing Management Service, Information Division, Food & Agriculture Organisation, United Nations, Rome.

Finnveden, G. (1997), Valuation Methods Within LCA – Where are the Values? *International Journal of Life Cycle Assessment*. 2 (3) 161 – 169

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Sangwon, S. (2009), Recent developments in Life Cycle Assessment. *Journal of Environmental Management*. 91, 1-21

Finnveden, G. & Moberg, A. (2005) Environmental Systems Analysis Tools - An Overview. *Journal of Cleaner Production* 13 1165-1173

Finnveden, G., Ostlund, P. (1997) Exergies Of Natural Resources In Life-Cycle Assessment And Other Applications. *Energy,* Vol. 22, No. 9, 923-931

Flood, R. L. (1995) Total Systems Intervention: A Reconstitution. *Journal of Operations Research Society*, 46**,** 174-191.

Flood, R. L. & Jackson, M. C. (1991) *Creative Problem Solving: Total Systems Intervention*, Chichester, Wiley.

Fluck, R. C. & Baird, C. D. (1980) *Agricultural Energetics,* Westport, Conn., AVI Pub. Co.

Forrester, J. W. (1961) *Industrial Dynamics,* Cambridge, MA., MIT Press.

Forrester, J. W. (1968) *Principles of Systems,* Cambridge, Massachusetts,

Wright-Allen Press.

Frater, T. G. (1999) *An Investigation into Innovation Management in the New Zealand Apple Production Industry*. Waikato University, Hamilton.

Frater, T. G. & Houston, D. J. (2008) Notes on Progress in Structuring a Research Project Measuring Energy Inputs into New Zealand Apple Production - Combining Hard and Soft Systems Methods. *Systems Research and Behavioural Science*, 25**,** 827-833.

Gaines, L. & Singh, M. (1995) Energy and Environmental Impacts of Electric Vehicle Battery Production and Recycling. *Total Life Cycle Conference.* Vienna, Austria, SAE.

Gaines, L. L. (1981) *Energy and Materials Use in the Production and Recycling of Consumer Goods Packaging*. US Dept. of Commerce, National Technical Information Service.

Geisler, G., Hofstetter, T. & Hungerbuhler, K. (2004) Production of Fine and Specialty Chemicals: Procedure for the Estimation of LCIs. *The International Journal of Life Cycle Assessment*, 9**,** 101-113.

Giampietro, M. (2004) *Multi-Scale Integrated Analysis of Agroecosystems*, London, CRC Press.

Giampietro, M., Bukkens, S. G. F. & Pimentel, D. (1994) Models of Energy Analysis to Assess the Performance of Food Systems. *Agricultural Systems*, 45.

Goh, K. M. & Haynes, R. J. (1983) Nutrient Inputs and Outputs in a Commercial Orchard and Their Practical Implications. *New Zealand Journal of Experimental Agriculture*, 11**,** 59-62.

Goodman, M. R. (1974) *Study Notes in System Dynamics,* Cambridge, MA., MIT Press.

Green, M. B. (1987) *Energy in Pesticide Manufacture, Distribution and Use*. IN Helsel, Z. R. (Ed.) Energy in Plant Nutrition and Pest Control. Amsterdam.

Griffiths, E. (1997) *Soil Map of the Heretaunga Plains*., Hawke's Bay Regional Council, Napier, NZ

Grosvenor, S., Heron, R. L. & Roche, M. (1995) Sustainability, Corporate Growers, Regionalisation and Pacific-Asia Links in the Tasmanian and Hawkes Bay Apple Industries. *Australian Geographer,* 26.

Guinée, J. B., Haes, H. A. U. D. & Huppes, G. (1993) Quantitative Life Cycle Assessment of Products. *Journal of Cleaner Production,* 1.

Guinée, J. B., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. D., Oers, L. V., Wegener, S. A., Suh, S., Udo De Haes, H. A., Bruijn, H. D., Duin, R. V. & Huijbregts, M. A. J. (2002) *Handbook on Life Cycle Assessment: Operational Guide to the Iso Standards,* Dordrecht, Kluwer

Gunther, F. (2002) Ruralisation - Integrating Settlements and Agriculture to Provide Sustainability. Urban Areas - Rural Areas and Recycling - the Organic Way Forward? *Proceedings from NJF- Seminar No. 327*, Copenhagen, Denmark, 20-21 August 2001.

Hackett, B., Chow, S. & Ganji, A. (2005) Energy Efficiency Opportunities in Fresh Fruit and Vegetable Processing/Cold Storage Facilities. *Summer Study on Energy Efficiency in Industry.* West Point, NY.

Han, H. & Gan, W. (2003) Energy Conservation of Ocean-Going Refrigerated Container Transportation. *International Congress of Refrigeration.* Washington DC, ICR.

Hannigan, J. (2006) *Environmental Sociology* (2nd Ed.) Routledge. London and New York.

Harvey, D. L. D. (2007) Net Climatic Impact of Solid Foam Insulation Produced with Halocarbon and Non-Halocarbon Blowing Agents. *Building and Environment,* 42**,** 2860-2879.

Hatirli, S., Ozkan, B., Fert, C. (2006) Energy Inputs and Crop Yield Relationship in Greenhouse Tomato Production. *Renewable Energy,* 31, 427–438

Hauff, V. (2007) Bruntland Report: A 20 Year Update. *European Sustainability, Berlin 07.* Berlin.

Heiskanen, E. (2002) The Institutional Logic of Life Cycle Thinking. *Journal of Cleaner Production.* 10 (2002) 427-437

Heller, M. C. & Keoleian, G. A. (2000*) Life Cycle-Based Sustainability Indicators for Assessment of the U.S. Food System.* Center For Sustainable Systems, University of Michigan. Ann Arbor,MI,

Hellstrom, T. (2003) Three Levels of Fuel Optimisation at Sea. *2nd International Euroconference on Computer and IT Applications in the Marine Industries.* Hamburg,

Helsel, Z. R. (1987) *Energy in Plant Nutrition and Pest Control,*Amsterdam, Elsevier.

Hines, P., Holweg, M. & Rich, N. (2004) Learning to Evolve: A Review of Contemporary Lean Thinking. *Journal of Operations and Production Management*, 24**,** 994-1011.

Hines, P. & Rich, N. (1997) The Seven Value Stream Mapping Tools. *International Journal of Operations and Production Management,* 17**,** 46-64.

Hjorth, P. & Bagheri, A. (2006) Navigating Towards Sustainable Development: A Systems Dynamics Approach. *Futures,* 38**,** 74-92.

Holb, I. J., De Jong, P. F. & Heijne, B. (2003) Efficacy and Phytotoxicity of Lime Sulphur in Organic Apple Production. *Annals of Applied Biology,* 142**,** 225-223.

Hunt, R. G. & Franklin, W. E. (1996) LCA - How It Came About. *International Journal of Life Cycle Assessment*, 1**,** 4-7.

Huntley, E. E., Barker, A. V. & Stratton, M. L. (1997) Agricultural Uses of by-Products and Wastes. *American Chemical Society Symposium Series.*

Hurrell, J. (1995) Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science,* 269**,** 676-9.

Hurrell, J. & Trenberth, K. (1994) Decadal Atmosphere-Ocean Variations in the Pacific. *Climate Dynamics,* 9**,** 303-19.

IEA (2005) *Energy Statistics Manual,* Paris, Organisation for Economic Co-operation and Development.

Imai, M. (1986) *Kaizen-the Key to Japan's Competitive Success*, Singapore, McGraw-Hill.

Imai, M. (1997) *Gemba Kaizen - a Commonsense, Low Cost Approach to Management*, Singapore, McGraw-Hill.

IPCC (2007) Summary for Policymakers. . IN Solomon, S. D., Manning, Q., M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L. (Eds.) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York,

Ison, R. L., Maiteny, P. T. & Carr, S. (1997) Systems Methodologies for Sustainable Natural Resources Research and Development. *Agricultural Systems.*

Jackson, M. C. (2000) *Systems Approaches to Management,* New York, Kluwer.

Jamieson, D. (2002) Morality's Progress: Essays on Humans, Other Animals, and the Rest of Nature, Oxford, Clarendon Press.

Jenkinson, D. S., Adams, D. E. & Wild, A. (1991) Model Estimates of CO_2 Emissions from Soil in Response to Global Warming. *Nature,* 351**,** 729-39.

Johnson, E. (2008) Disagreement over carbon footprints: A comparison of electric and LPG forklifts. *Energy Policy*, 36, 1569-1573

Johnson, G. L. (1984) Ethics, Economics, Energy, and Food Conversion Systems. IN Pimental, D. & Hall, C. W. (Eds.) *Food and Energy Resources.* Orlando, Fl, Academic Press.

Jones, A. (2002) An Environmental Assessment of Food Supply Chains: A Case Study on Dessert Apples. *Environmental Management,* 30.

Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C. & Richter, K. (2002) Allocation in LCA of Wood-Based Products. *International Journal of Life Cycle Assessment,* 7**,** 290-294.

King, M. (2003) *The Penguin History of New Zealand*, Auckland, Penguin.

Kytzia, S., Faist, M., Baccini, P. (2004) Economically Extended — MFA: a Material Flow Approach for a Better Understanding of Food Production Chain. *Journal of Cleaner Production*. 12, 877–889

Kupferman, E. (1984) Waxing Red Delicious. *Post Harvest Pomology Newsletter*, 2**,** 8-15.

Kutz, M. (2004) *Handbook of Transportation Engineering*, Mcgraw-Hill.

Lal, R. (2004) Soil Carbon Sequestration Impacts on Global Climate

Change and Food Security. *Science,* 304**,** 1623-1627.

Lancester, R. (2000) The Design Limit State of Environmental Sustainability. *International Conference on Marine Engineering Systems,* United States Merchant Marine Academy, New York*,*

Lenzen, M. (1999) Total Requirements of Energy and Greenhouse Gases for Australian Transport. Transportation Research Part D: *Transport and the Environment*, 4**,** 265-290.

Lenzen, M. (2002) A Guide for Compiling Inventories in Hybrid Life-Cycle Assessments: Some Australian Results. *Journal of Cleaner Production,* 10**,** 545-572.

Li, F., Cohen, S., Naor, A., Shaozong, K. & Erez, A. (2002) Studies of Canopy Structure and Water Use of Apple Trees on Three Rootstocks. *Agricultural Water Management,* 55**,** 1-14.

Long, S. (1991) Modification of the Response of Photosynthetic Productivity to Rising Temperature by Atmospheric CO_2 Concentrations—Has Its Importance Been Underestimated. *Plant Cell and Environment* 14**,** 729-39.

Lovelock, J. E. (1989) Gaia. *Journal of Marine Biology Association*. UK, 69**,** 746-758.

Luke, J. (Ed.) (1968a) *Soils of New Zealand Part 1*, N.Z. Soil Bureau.

Luke, J. (Ed.) (1968b) *Soils of New Zealand Part 2*, N.Z.Soil Bureau.

Madsen, M. (2007) The Role of Biomass in the Future Global Energy Supply. *The 20th World Energy Congress*,. Rome.

MAF (2005) *Agriculture Forestry Horticulture in Brief*. New Zealand Ministry of Agriculture and Forestry.

MAF (2007) Horticultural and Arable Monitoring Report. *Policy Publications* (MAF).

Malavasi, F. F. F., Mazza, A., & Dodi, S. (1983). "Energy characteristics of pruning residues." *Rivista della Ortoflorofrutticoltura Italiana* 67(4).

Mattsson, B. (1999) Environmental Life Cycle Assessment (LCA) of Agricultural Food Production. Acta Universitatis Agriculturae Sueciae - *Agraria*. 187.

McChesney, I. G. (1980) *Energy Use on Hill Country Sheep and Beef Farms near Cheviot, North Canterbury*. Centre for Resource Management. Lincoln, N.Z.

McChesney, I. G. (1991a) *The Brundtland Report and Sustainable Development in New Zealand*, Centre for Resource Management. Lincoln, N.Z.

McChesney, I. G. (1991b) *From Threat to Opportunity : Moving to a Sustainable Energy Pathway*, Centre for Resource Management. Lincoln, N.Z.

McClintic, C. (2008) Fuels from the Forest Floor. *Powersource.*

McKenna, M., Le Heron, R. & Roche, M. (2001) Living Local, Growing Global: Renegotiating the Export Production Regime in New Zealand's Pipfruit Sector. *Geoforum,* 32.

McKenna, M., Roche, M. & Heron, R. L. (1998) Sustaining the Fruits of Labour: A Comparative Localities Analysis of the Integrated Fruit Production Programme in New Zealand's Apple Industry. *Journal of Rural Studies*, 14.

McKenna, M., Roche, M. & Heron, R. L. (1999) *An Apple a Day:*

Renegotiating Concepts, Revisiting Context in New Zealand's Pipfruit Industry. IN Restructuring Global and Regional Agricultures: Transformations in Australasian Agri-Food Economies and Spaces (Conference proceedings)

McKenzie, D. W. (Ed.) (1987) *Heinemann New Zealand Atlas,* Auckland, Reed.

McLaughlin, N.B., Hiba, A., Wall, G.J., King, D.J. Comparison of Energy Inputs for Inorganic Fertilizer and Manure Based Corn Production. *Canadian Agricultural Engineering.* 42, 1

Melnick, D., McNeely, J., Navarro, Y. K., Schmidt-Traub, G. & Sears, R. R. (2005) UN Millenium Project 2005. *Environment and Well-being: A Practical Strategy.* Summary Version of the Report of the Task Force on Environmental Sustainability. New York, The Earth Institute at Columbia University.

Merts, I. & Cleland, D. (2004) *Survey of Energy Use by the New Zealand Cold Storage Industry.* Energy Efficiency and Conservation Authority, New Zealand Cold Storage Association. Palmerston North, NZ

Midgley, G. (1997) Developing the Methodology of TSI: From the Oblique Use of Methods to Creative Design. *Systems Practice,* 10.

Midgley, G. (2000) *Systemic Intervention : Philosophy, Methodology, and Practice.* Kluwer, New York :,

Midgley, G. (2003) Science as Systemic Intervention: Some Implications of Systems Thinking and Complexity for the Philosophy of Science. *Systemic Practice and Action Research*, 16.

Mila` i Canals, L. (2003) *Contributions to LCA Methodology for Agricultural Systems. Site-Dependency and Soil Degradation Impact Assessment*. Barcelona, Autonoma.

Mila` i Canals, L., Burnip, G. M. & Cowell, S. J. (2006) Evaluation of the Environmental Impacts of Apple Production Using Life Cycle Assessment (LCA): Case Study in New Zealand. *Agriculture, Ecosystems and Environment*, 114**,** 226–238.

Mila` i Canals, L. & Clemente Polo, G. (2003) *Life Cycle Assessment of Fruit Production*. IN Environmentally-Friendly Food Processing. Woodhead Publishing Ltd.

Mila` i Canals, L., Cowell, S. J., Sim, S. & Basson, L. (2007) Comparing Domestic Versus Imported Apples: A Focus on Energy Use. *Environmental Science and Pollution Research*, 14**,** 338-44.

Mitchell, J. F. B., Johns, T. C., Gregory, J. M. & Tett, S. F. B. (1995) Climate Response to Increasing Levels of Greenhouse Gases and Sulfate Aerosols. *Nature,* 376 501-4.

Mitroff, I. I. & Emshoff, J. R. (1979) On Strategic Assumption Making: A Dialectic Approach to Policy and Planning. *The Academy of Management Review*, 4**,** 1-12.

Mohan, D., Pittman, C. U., Steele, P. H. (2005). Pyrolysis of Wood/Biomass for Bio-Oil: A Critical Review. *Energy and Fuels*: 848-889.

Montushi, E. (2001) *Metaphor in Science. A Companion to the Philosophy of Science*. Wiley-Blackwell.

Moon, B. W., Choi, J. S. & Park, M. Y. (1998) Effects of Calcium Compounds Extracted from Oyster Shell on the Calcium Content in Apple Fruits   *Journal of the Korean Society for Horticultural Science,* 39**,** 454-459.

Morecroft, J. D. W. (1982) A Critical Review of Diagraming Tools for Conceptualizing Feedback System Models. *Dynamica*.

MoRST-SLURI (2004) *Soil Management and Land Use: Priorities and Science Imperatives*. Ministry of Research, Science and Technology, Sustainable Land Use Research Initiative

Mudahar, M. S. & Hignett, T. P. (1987) *Energy Requirements, Technology and Resources in the Fertilizer Sector*. IN Helsel, Z. R. (Ed.) Energy in Plant Nutrition and Pest Control . Energy in World Agriculture, 2. Amsterdam, Elsevier

Nielsen, A. M. & Weidema, B. P. (2001) *Input/Output Analysis - Shortcuts to Life Cycle Data?*, Danish Environmental Protection Agency. Copenhagen

Nonaka, I. & Takeuchi, H. (1995) *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation,* New York, Oxford University Press.

Ny, H. (2006) *Strategic Life-Cycle Modeling for Sustainable Product Development,* Karlskrona, Sweden, Blekinge Institute of Technology.

Palmer, W. J. & Dryden, G. (2006) Fruit Mineral Removal Rates from New Zealand Apple (*Malus Domesticus*) Orchards in the Nelson Region. New Zealand. *Journal of Crop and Horticultural Science*, 34**,** 27-32.

Parr, J. F. & Colacicco, D. (1987) *Organic Materials as Alternative Nutrient Sources*. IN Helsel, Z. R. (Ed.) Energy in Plant Nutrition and Pest Control. Amsterdam, Elsevier.

Pickering, A. (2002) Cybernetics and the Mangle. *Colloquium - Centre Koyre.* Paris.

Pimentel, D. (1980) *Handbook of Energy Utilization in Agriculture,*.CRC Press. Boca Raton, Fl.

Pimentel, D. & Hall, C. (1984) *Food and Energy Resources,* Academic Press. Orlando. Fl.

Poe, A. (2003) An Energy Analysis of Organic and Conventional Apple

Production. *Environmental Studies*. Lewiston, Bates College.

Polanyi, M. (1958*) Personal Knowledge: Toward a Post-Critical Philosophy,* Chicago, University of Chicago Press.

Polanyi, M. (1966) *The Tacit Dimension,* London, Doubleday and Co.

Popper, K. R. (1972) *Objective Knowledge - an Evolutionary Approach*, London, Oxford University Press.

Porter, M. (1985) *Competitive Advantage - Creating and Sustaining Superior Performance*, New York, Free Press.

Pretty, J., N., Ball, A. S., Lang, T. & Morison, J. I. L. (2005) Farm Costs and Food Miles: An Assessment of the Full Cost of the UK Weekly Food Basket. *Food Policy,* 30**,** 1-19.

Rao, A., Carr, L., Dambolena, I., Kopp, R., Martin, J., F., R. & P., S. (1996) *Total Quality Management: A Cross Functional Perspective,* John Wiley and Sons, New York

Reed, T.B. & Das, A. (1988) *Handbook of Biomass Downdraft Gasifier Engine Systems*, Biomass Energy Foundation Press, Franktown, Denver.

Reganold, J. P., Glover, J. D., Andrews, P. K. & Hinman, H. R. (2001) Sustainability of Three Apple Production Systems. *Nature.* 410**,** 926-930.

Rice, G., Clift, R. & Burns, R. (1997) Comparison of Currently Available European LCA Software. *The International Journal of Life Cycle Assessment*, 2**,** 53-59.

Riesinger, P. (1999) *Efficient and Sustainable Agriculture. Perspectives Based on a Study of Lithuania and Its Agriculture*. Tidskrift/serie: Examensarbeten/Seminarieuppsatser Sveriges Lantbruksuniversitet.

Rigby, D. & Bown, S. (2003) *Organic Food and Global Trade: Is the Market Delivering Agricultural Sustainability*. University of Manchester

Rigby, D. & Bown, S. (2007) Whatever Happened to Organic? Food, Nature and the Market For "Sustainable" Food. *Capitalism Nature Socialism,* 18**,** 81-102.

Rizet, C., Browne, M., Cornelis, E. & Leonardi, J. (2008) Energy Efficiency and Greenhouse Gas Emissions of Different Supply Chains: A Comparison of French, UK and Belgian Cases. *European Transport Conference.* Leiden, The Netherlands.

Robert, K.-H., Daly, H., Hawken, P. & Holmberg, J. (1997) A Compass for Sustainable Development. *International Journal of Sustainable Development and World Ecology*, 4**,** 79-92.

Rolston, H. (1996) *Feeding People Versus Saving Nature?* IN Aitken, W. & Lafollette, H. (Eds.) World Hunger and Morality. Englewood Cliffs, Prentice Hall.

Rosen, R. (1985) *Theoretical Biology and Complexity: Three Essays on the Natural Philosophy of Complex Systems*, , Academic Press. Orlando, FL

Rosenhead, J. & Mingers, J. (2001) *Problem Structuring Methods for Complexity, Uncertainty and Conflict*, Chichester, John Wiley and Sons.

Rothman, S. & Lichter, S. R. (1987) Elite Ideology and Risk Perception in Nuclear Energy Policy. *American Political Science Review*, 81.

Routley, R. (1973) Is There a Need for a New Environmental Ethic? *15th World Congress of Philosophy.* Sophia, Sophia Press

Rydberg, T., Frankenhaeuser, M., Lundahl, L., Otto, T., Swan, G., Tanner, T. & Hansen, O. J. (1995) *LCA of the Tetra Brik Milk Packaging System - Product and Process Development Options for Improved Environmental Performance*. CIT-Ekologik Report.Goteborg.

Saunders, C., Barber, A. & Taylor, G. (2006) *Food Miles : Comparative Energy/Emissions Performance of New Zealand's Agricultural Industry*. :, Agribusiness & Economics Research Unit, Lincoln University, NZ.

Schaeffer, F. A. (1970) *Pollution and the Death of Man - the Christian View of Ecology,* Tyndale, Wheaton, Illinois.

Scully, G.W. (1998) Reform and Efficiency Gains in the New Zealand Electrical Supply Industry. *Journal of Productivity Analysis*, 11, 133-147

SEAV (2002) *Energy Smart Coolstore Operation. A Study of Energy Use by Coolstore Operators.* Sustainable Energy Authority Melbourne Victoria.

Selke, S. E. (1999) *Packaging Options*. IN Dalzell, J. (Ed.) Food Industry and the Environment in the European Union.

Simons, D. & Mason, R. (2003) Lean and Green: 'Doing More with Less'. *ECR Journal*, 3**,** 84-91.

Sims, R. E. H. & Henderson, P. (1984) Direct Energy Substitution and Conservation in Industrialised Agricultural Production with Particular Relevance to New Zealand. *Energy in Agriculture,* 3.

Sims, R. E. H., Young, R. W. J. & Martin, G. A. (1988) Tractor Efficiency and Fuel Conservation - a New Zealand Approach to Farm Advisory Work. *Agricultural Engineer,* 43.

Smith, A., Watkiss, P., Tweddle, G., Mckinnon, A., Browne, M., Hunt, A., Treleven, C., Nash, P. C. & Cross, S. (2005) *The Validity of Food Miles as an Indicator of Sustainable Development: FinalReport*. DEFRA. UK.

Smith, D. J. (1979) *A Review of Energy Use in New Zealand Agriculture, Energy Research and Development Committee*. Auckland, New Zealand

Smith, T. M. & Shugart, H. H. (1993) The Transient Response of Terrestrial Carbon Storage to a Perturbed Climate. *Nature,* 361**,** 523-6.

Stadig, M. (2001) *Life Cycle Assessment of Apple Production- Case Studies from Sweden, New Zealand and France*. SIK.report 630. Swedish Institute for Food and Biotechnology

Stone, C. D. (1972) Should Trees Have Standing? *Southern California Law Review,* 45**,** 450-501.

Thompson, J. (2001) Energy Conservation in Cold Storage and Cooling Operations. *Perishables Handling Quarterly*. 105, 7-9

Toyota (2001) *Development of Environmentally Concious Products (LCA of Electric and Diesel Forklifts).* Toyota Industrial Equipment.

Tukker, A. (1999). *Frames in the toxicity controversy. Risk assessment and policy analysis related to the Dutch chlorine debate and the Swedish PVC debate*. Kluwer Academic Publishers, Dordrecht/Boston/London.

Tukker, A. (2000). Philosophy of science, policy studies and the basis of decision support with LCA. *International Journal of LCA*. 5 (3) 177 – 186

Tukker, A. (2002). Risk Analysis, Life Cycle Assessment-The Common Challenge of Dealing with the Precautionary Frame (Based on the Toxicity Controversy in Sweden and the Netherlands). *Risk Analysis,* 22 (5)

Ulrich, W. (1986) *Critical Heuristics of Social Systems Design. Working Paper #10.* Hull, Department of Management Systems and Sciences, University of Hull.

Ulrich, W. (1987) Critical Heuristics of Social Systems Design. *European Journal of Operational Research*, 31**,** 276-283.

Ulrich, W (1993) Some Difficulties of Ecological Thinking, Considered from a Critical Systems Perspective: A Plea for Critical Holism. *Systems Practice*, 6 (6)

Ulrich, W. (2001) The Quest for Competence in Systemic Research and Practice. *Systems Research and Behavioural Science*, 18**,** 3-28.

Ulrich, W. (2002a) *Critical System Heuristics*. IN Daellenbach, H. G. & Flood, R. L. (Eds.) The Informed Student Guide to Management Science. Thomson. London

Ulrich, W. (2002b) *Boundary Critique*. IN Daellenbach, H. G. & Flood, R. L. (Eds.) The Informed Student Guide to Management Science. Thomson. London

Ulrich, W. (2005) A Brief Introduction to Critical Systems Heuristics (CSH)., *Ecosensus* (Electronic/Ecological Collaborative Sense-making Support System). Milton Keynes, UK

UN (1987) *Report of the World Commission on Environment and Development to the UN General Assembly*. UNDESA.

Upham, P. (2000) An Assessment of the Natural Step Theory of Sustainability. *Journal of Cleaner Production,* 8**,** 445–454.

van Buren, A. *A Chinese Biogas Manual: Popularising Technology in the Countryside*. Intermediate Technology Publications, London

van der Werf, H. M. G. & Petit, J. (2002) Evaluation of the Environmental Impact at the Farm Level: A Comparison and Analysis of 12 Indicator-Based Methods. *Agriculture, Ecosystems & Environment*, 93**,** 131-145.

Venturi, P. & Venturi, G. (2003) Analysis of Energy Comparison for Crops in European Agricultural Systems. *Biomass and Bioenergy*, 25, 235-255.

Vidal, R. V. V. (2006) Operational Research: A Multidisciplinary Field. *Pesquisa Operacional*,, 26**,** 69-90.

Von Bertananffy, L. (1950) An Outline of General Systems Theory. *British Journal of the Philosophy of Science*, 1**,** 134-165.

Webb, R. (2004) *Coastal Shipping: An Overview*. Department of Parliamentary Services Research Paper no. 12, 2003-04. Aus.

Weidema, Bo P., Thrane, M., Christensen, P., Schmidt, J., Løkke, (2008) Carbon Footprint – a Catalyst for Life Cycle Assessment. *Journal of Industrial Ecology*, 12, 1

Wells, C. M. (2001) *Total Energy Indicators of Agricultural Sustainability : Dairy Farming Case Study Ministry of Agriculture and Forestry*. Wellington N.Z

Wenzel, H., Hauschild, M. & Alting, L. (1997) *Environmental Assessment of Products. Methodology, Tools, Techniques and Case Studies in Product Development*,, London, UK, Chapman & Hall,.

Werner, F. (2005) *Ambiguities in Decision-Orientated Life Cycle Inventories*, Dordrecht, Springer.

Wiegard, J. (2001) *Quantification of Greenhouse Gases at Visy Industries Using Life Cycle Assessment*. School of Engineering and Science. , University of Technology. Swinburne University, Melbourne, Aus.

Wild, Y. (1995) Porthole Vs Integral Reefer Containers. *Intermodal Conference*.

Wild, Y. (2008) *Container Handbook.* IN Refrigerated Containers and CA Technology. Gesamtverband der Deutschen Versicherungswirtschaft e V. (GDV).

Wilson, R. (2005) The Pipfruit Sector - Where to from Here. *Primary Industry Management*, 8**,** 18-19.

Winter, M. (2003) Embeddedness, The New Food Economy, and Defensive Localism. *Journal for Rural Studies*. 19, 1. 23-32.

Womack, J. P. & Jones, D. T. (1996) *Lean Thinking*. Simon and Schuster

Wright, P. G., Mckinlay, P. R. & Shaw, E. Y. N. (1992) *Corrugated Fibre Boxes - Their Design, Use, Quality Control and Testing*. Camberwell, Victoria, Australia, Amcor Fibre Packaging.

Yakovleva, N., Flynn, A., Green, K., Foster, C. & Dewick, P. (2004) A Sustainability Perspective: Innovations in the Food System. *Joint 4S/EASST Conference 2004 Public proofs – sciences, technology and democracy,* Paris, BRASS Research Centre, Cardiff University, 54 Park Place, Cardiff; CROMTEC / Institute of Innovation Research, Manchester.

Zhang, Q., Chang, J., Wang, T. & Xu, Y. (2006) Review of Biomass Pyrolysis Oil Properties and Upgrading Research. *Energy Conversion and Management,* 48.

Web Reference	Retrieved
Giantbatteryco (2009)	
http://giantbatteryco.com/gbweb/BatterySelector/Misubishi.xls	30-11-09
http://www.unu.edu	30-2-06