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Eco-efficiency as a sustainability measure for kiwifruit production in New Zealand

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ABSTRACT

Assessing the sustainability of orchards focuses on quantifying environmental impacts and resource consumption. Sustainable orchards also have to be profitable and socially responsible. We aimed to identify sustainable kiwifruit production in the Bay of Plenty, New Zealand, by considering orchards' environmental and economic performance. We conducted a survey of 40 orchards with different cultivars (*Actinidia deliciosa* 'Hayward' (green) v. *Actinidia chinensis* 'Hort16A' (gold)) and management (integrated v. BioGro certified organic). Assessment of environmental performance was restricted to greenhouse gas emissions (carbon footprint of the orchard phase). We defined eco-efficiency on an area basis as NZD net profit per kg greenhouse gas emissions (1 NZD = 0.83 USD, 31/10/2013). Carbon footprints for the cultivars and management systems were comparable. The choice of functional unit, namely land area and 1 kg of produce, did not affect the result. Our analysis revealed fertilizer use and the N-associated emissions as hot spots for greenhouse gas emissions. Opportunities to reduce greenhouse gas emissions arise in the background system of fertilizer production, packaging, storage and transport, and the optimization of nutrient-use efficiency in the orchard. The integrated system had insignificantly higher greenhouse gas emissions than the organic system. Taking into account the profitability of the orchards, the eco-efficiency of organic orchards was significantly higher than that of integrated orchards. We demonstrated that the metric of eco-efficiency can enhance product differentiation for customers and can also assist orchardists to find the most sustainable management system. However, the volatility of commodity markets and changing consumer preferences remain challenges.

1. Introduction

Assessing the sustainability of orchard systems generally focuses on quantifying environmental impacts such as nutrient, pesticide, and sediment losses to aquatic ecosystems, greenhouse gas emissions to the atmosphere, resource consumption including water and energy use, and fertilizer input. The recent evaluation of the water footprint of New Zealand kiwifruit production (Deurer et al., 2011), or the life cycle assessment of New Zealand apple production (Mila i Canals et al., 2006) are examples. However, sustainability evaluations of orchards need to be extended beyond simply environmental impacts. Sustainable orchards also have to be profitable and socially responsible in the longer term.

Eco-efficiency is an improved measure of sustainability because it links environmental impacts directly with some kind of economic performance. The concept of eco-efficiency was first introduced by Schaltegger and Sturm (1989). It encompasses the idea of 'creating more value with less impact' (Lehni, 2000). Other authors reversed the ratio, and reported the economic value-added per unit of environmental impact as eco-efficiency (e.g., Meul et al., 2007a). There are no agreed-upon methods and tools for calculating eco-efficiency (Huppes and Ishikawa, 2005). This implies that eco-efficiency claims for products and services need to be critically assessed (Ehrenfeld, 2005). Environmental impacts for eco-efficiency calculations usually include energy use, resource use, water use, greenhouse gas (GHG) emissions and ozone-depleting emissions (Verfaillie and Bidwell, 2000). The concept of eco-efficiency has so far been mainly used by industrial businesses to support economic decisions such as assessing acquisitions and

Abbreviations: GHG, greenhouse gas.

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changes in product lines, as well as to create new market opportunities by demonstrating stewardship for natural resources (Saling et al., 2002). It can also be applied to decision-making problems in agriculture, for example, in relation to irrigation and crop protection management decisions (de Jonge, 2004; Meul et al., 2007a, 2007b; Wießner et al., 2010). Applications, challenges and opportunities of the general concept to agricultural production systems have recently been reviewed by Keating et al. (2010).

Kiwifruit is the fruit of a perennial woody vine and is of considerable importance for New Zealand's economy. New Zealand developed the first commercially viable kiwifruit in 1937, and nowadays the country is amongst the leading kiwifruit producing countries worldwide. Kiwifruit production totalled about 1,412,351 MT in 2012 with Italy and New Zealand producing together about 54% of this total (http://faostat.fao.org/site/339/default.aspx). Kiwifruit is one of New Zealand's highest earning horticultural exports. Export earnings for New Zealand grown kiwifruit were $1.122 billion over the 2011-12 year. The largest population of kiwifruit worldwide is the *Actinidia deliciosa* cultivar Hayward, a green-fleshed fruit. In New Zealand, 9336 ha of *A. deliciosa* Hayward is under integrated management, and 576 ha grown according to BIO-GRO organic standards. For *Actinidia chinensis* Hort16A, a gold-fleshed fruit, the areas total 2590 ha (Zespri Group Limited Annual Review, 2012; http://www.zespri.com/about-zespri/zespri-investors/investor-publications.html).

Management practices designed for carbon storage in kiwifruit orchards, and other perennial tree crops, are potential tools for New Zealand growers to mitigate and adapt to the consequences of climate change. In particular, growers in existing growing regions will need to be more resilient to climate related impacts associated with warmer temperatures, scarcer water resources and a greater risk of extreme storm events. National and international initiatives to reduce rising atmospheric concentrations of greenhouse gases include encouraging growers and other value chain stakeholders to reduce the GHG emissions associated with the production of their products and services. Changes in management methods could enable growers to meet eco-verification market demands for products with a low carbon footprint, and potentially exploit the emerging business opportunity in carbon storage.

The objectives of our study were threefold: (1) to compare the environmental impacts in the form of GHG emissions arising from organic and integrated kiwifruit production and to identify management operations which have the highest impact in the systems studied, namely hot spots for GHG emissions; (2) to compare the environmental performances of different kiwifruit cultivars, and; (3) to combine the results of the environmental assessments with profitability data and calculate eco-efficiencies for the different kiwifruit production systems. In our study, the eco-efficiency ratio answers the question of how much net value is added to the grower per kg of GHG emitted to the atmosphere.

2. Material and methods

2.1. Survey of kiwifruit orchards

In New Zealand, 77% of the total canopy area of kiwifruit (12,825 ha; http://www.freshfacts.co.nz/file/fresh-facts-2011.pdf) is located in the Bay of Plenty region of the North Island (http://www.stats.govt.nz/browse_for_stats/industry_sectors/agriculture-horticulture-forestry/

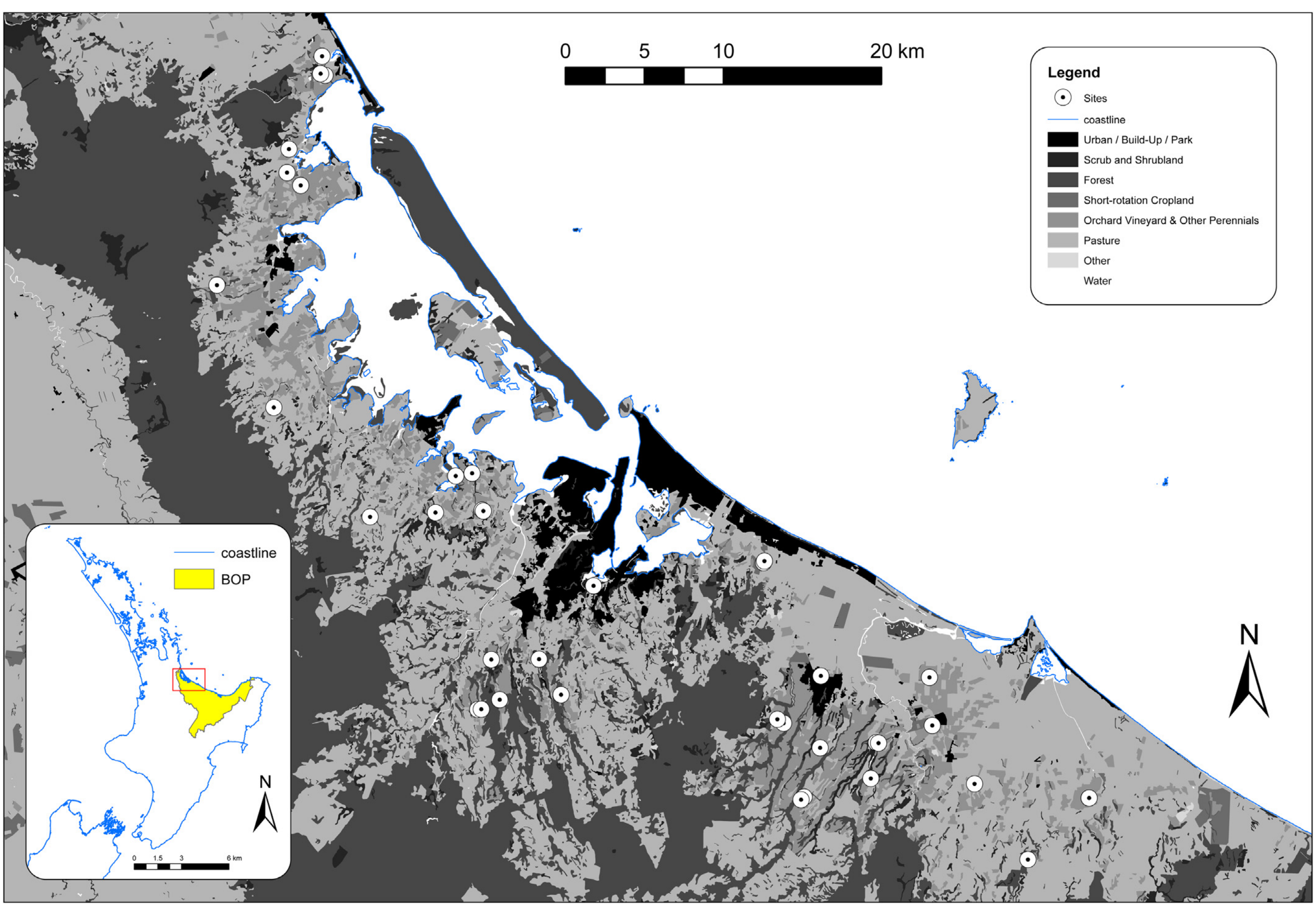

Fig. 1. Location of the 40 kiwifruit orchards in the Bay of Plenty (BOP) region, New Zealand that participated in the one-year survey on orchard practices.

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AgriculturalProduction_HOTPJun07final.aspx), and 84% of kiwifruit in New Zealand is produced in this region (Kilgour et al., 2008). We concentrated on this region with its prime importance for kiwifruit production in New Zealand and we conducted a one-year survey including 40 representative kiwifruit orchards in the Bay of Plenty (Fig. 1). The survey was limited to kiwifruit grown on pergola structures, which, at 99%, dominates New Zealand kiwifruit production systems. Furthermore, we restricted our survey to the current and productive phase of mature orchards, thereby omitting the potential costs and benefits of the establishment phase of orchards. It has to be noted that this approach could lead to an underestimation of an environmental indictor of perennial orchards as shown for the ecological footprint (Cerutti et al., 2010). The experimental design of the survey was a completely randomized block design with two factors. The primary factor was the management system (integrated, organic BIO-GRO). The secondary factor was the kiwifruit cultivar (*A. deliciosa* 'Hayward', or *A. chinensis* 'Hort16A'). 'Hort16A' (developed in New Zealand and marketed as Zespri® Gold Kiwifruit) has golden yellow flesh, with a less tart and more tropical flavour than the green 'Hayward' kiwifruit (marketed as Zespri® Green Kiwifruit). Our final survey included 20 integrated and 20 organic kiwifruit orchards. Within each management system, ten of the orchards grew 'Hort16A', and the remaining ten produced 'Hayward'.

Seventeen of the selected orchards were located in the Te Puke district. The average annual temperature, relative humidity and cumulative precipitation (average; ± one standard deviation; $n = 30$ years) were, 14.5 ± 0.4 °C, 81 ± 1%, and 1366 ± 249 mm, respectively. The Tauranga district had 14 orchards (temperature, 14 ± 0.5 °C, relative humidity, 83 ± 1%, precipitation, 1733 ± 278 mm) Katikati and Waihi districts respectively had six selected orchards (temperature, 14.5 ± 0.4 °C, relative humidity, 82 ± 1%, precipitation, 1657 ± 264 mm) and three orchards (temperature, 14.7 ± 0.4 °C, relative humidity, 82 ± 1%, precipitation, 1753 ± 273 mm). All selected orchards were on free-draining Andosols (Allophanic Orthic Pumice soils (Hewitt, 1998)) which were formed predominantly from ryolitic tephra between 4000 and 40,000 years ago during the region's geologic history of periodic volcanic eruptions.

Data on orchard production practices were gathered through a comprehensive questionnaire sent out to the orchardists. Follow-up interviews were conducted in August 2010. The questionnaire covered several topics, including production, general orchard information (fuel and electricity use) and cultivar-specific management practices and the various inputs related to those activities (organic and inorganic fertilizers, pesticides, lime etc.). In addition, the economics of kiwifruit production were inventoried (Table 1). All economic data were based on expert knowledge and information provided by the orchardists in the survey, and Zespri International Limited, the global kiwifruit marketing organization in New Zealand.

2.2. Calculation of the carbon footprint of kiwifruit production

The reduction of GHG emissions is one the most urgent environmental challenges of agricultural production systems. Greenhouse gas emissions lead to climate change. The latest report of the Intergovernmental Panel on Climate Change delivers the strong message that 'The evidence for human influence has grown … It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century' (Intergovernmental Panel on Climate Change (IPCC), 2013). The production of GHG emissions is related to the use of fossil fuels, intensive livestock production, and fertilizer use. In this paper, GHG emissions were therefore used as a proxy for the global environmental impact caused by kiwifruit production.

The carbon footprint of kiwifruit production is defined as the sum of all GHGs emitted during the life cycle or part of the life cycle of kiwifruit production. It is expressed as CO_2 equivalents (CO_2e). Carbon dioxide equivalent is defined as a measure used to compare the emissions from various GHGs based upon their global warming potential (IPCC, 2001). Our estimation of the carbon footprint of kiwifruit production followed the PAS 2050 methodology (BSI, 2011). We conducted a life cycle assessment (LCA) to evaluate and compare GHG emissions related to producing kiwifruit under different management systems and kiwifruit cultivars.

2.2.1. System boundaries

We decided to concentrate on the orchard phase of kiwifruit production and truncated the system boundaries at the farm gate (cradle-to-farm-gate). Consequently, all processes related to the transport, packing and marketing downstream from the farm gate, as well as consumption and waste handling phases, were excluded from our analysis. The total GHG emissions released for a tray equivalent of New Zealand kiwifruit consumed by a consumer in the UK were estimated to be 5.326 kg CO_2e, of which 13% were related to the orchard phase (Mithraratne et al., 2008). Nevertheless, in addition to the agricultural management activities of the growers, the emissions of relevant up-stream activities (indirect emissions), such as the production, processing and import of mineral fertilizers and pesticides, were considered. GHG emissions related to capital goods such as machinery and buildings were excluded from the assessment, following the guidelines PAS 2050 (BSI, 2011). The reasoning for selecting the farm gate as system boundary was driven by our first two objectives, namely to identify hot spots for GHG emission in the orchard management to guide growers to more sustainable kiwifruit production.

Table 1
Overview of main survey questions to the growers of the 40 representative kiwifruit orchards located in the Bay of Plenty, New Zealand.

General information	Size of orchard block (canopy area of certain cultivar)
	Orchard design
	Planting date of kiwifruit
	Grafting date of kiwifruit
	Sward and shelterbelt composition
	Physical changes to orchard during 2010
	Soil or leaf tests for fertilizer applications
	Production data for harvest 2010 for different classes of fruit
	Production data for mature stages of orchard
Capital equipment	Machinery
	Vehicles
	Growing structure and support in orchard
	Irrigation equipment
Activities – involving fuel & electricity usage	Total fuel and electricity usage
	Mowing (number of passes; tractor; contractor)
	Spraying (number of passes; tractor; contractor)
	Shelter trimming (number of passes; tractor; contractor)
	Mulching (number of passes; tractor; contractor)
	Fertiliser application (number of passes; tractor; contractor)
	Irrigation
	Soil cultivation
	Sward management
	Girdling
	Others not listed
Fertiliser applications	Ground – and foliar-applied fertilisers
	Type, name of product, amount and date of applications for each cultivar
Agrichemical applications	Type, name of agrichemical, amount and date of applications for each cultivar

2.2.2. Functional unit

We chose to compare GHG emissions in terms of both the area (ha) and mass (kg) of kiwifruit produced. Former studies (de Backer et al., 2009) showed that different results might be obtained depending on the functional unit chosen. This highlights the multi-functional role of agriculture. If the functional unit is 1 kg of produce, the focus of the carbon footprint analysis is the production of produce of a defined quality. However, if land area is chosen as functional unit, the objective of the assessment is the environmental impact on a local area. This definition relates to the function of agriculture as a guardian of environmental services that soils provide.

2.2.3. Inventory analysis

Management operations in kiwifruit orchards associated with high GHG emissions, including pest and disease management, soil management, weed control and fertilization, were considered in our inventory analysis (Table 2). The estimation of GHG emissions from management operations in the orchard can be divided into two sub-systems, a background and a foreground system (Mila i Canals et al., 2006). Our background system of the inventory analysis of kiwifruit production included the production of fertilizers and agrichemicals, related energy carriers and transportation. The foreground system consisted of the actual operations in the orchard.

2.2.4. Background system

As part of the background system, we estimated the amount of energy used for producing, packaging, storing, transporting, and importing fertilizers and pesticides (herbicides, insecticides, fungicides) to a port in New Zealand, and we approximated the resulting GHG emissions. Our inventory analysis for pesticides was based on a recent specific assessment for pesticides used in New Zealand kiwifruit production (Müller et al., 2011). In brief, we conducted a survey of pesticide suppliers that consisted of interviewing representatives of the New Zealand chemical industry relevant for kiwifruit production, to determine the offshore production sites of the active ingredients, the sites of formulation, and the transport routes and means to the port of Auckland, New Zealand. We followed the ILCD handbook (International Reference Life Cycle Data System (ILCD), 2010) using the information from this survey, and additional information (e.g., concentration of active ingredients, formulation) from product labels. We produced a GHG inventory for all pesticides used in kiwifruit production systems using Life Cycle Inventory (LCI) databases published by the Swiss Centre for Life Cycle Inventories, ecoinvent v.2.2. (2010). Similarly, New Zealand- and kiwifruit-specific GHG inventories were available for the two fertilizers of muriate of potash and calcium ammonium nitrate (Zonderland-Thomassen et al., 2011). Data associated with background operations for all other fertilizers were taken from the Life Cycle Inventory (LCI) databases published by the Swiss Centre for Life Cycle Inventories, ecoinvent v.2.2. (2010).

2.2.5. Foreground system

Information on the operations in the foreground systems was extracted from our survey. The calculation of the GHG emissions associated with the production and combustion of fossil fuels used for all management operations in the orchard was based on the time schedules of the orchardists. The diaries included the frequency of an operation per year, the duration of each operation and the fuel consumption per hour of each operation. Using an emission factor of 3.11 kg CO_2e for the production and combustion of one litre of diesel (Mithraratne et al., 2008), the GHG emissions associated with the fuel used on an orchard during a production year were calculated. Some tractors used petrol, so a conversion factor from petrol to diesel was used. Electricity was mainly used for irrigation in the orchards. However, irrigation of kiwifruit is negligible in this region; there are large amounts of plant-available water in soils under kiwifruit orchards because the effective rainfall is significantly larger than the evapotranspiration rates, and because of the high water storage capability of Andosols, the predominant soils in the region (Deurer et al., 2011). Moreover, data on electricity usage were not readily available, so GHG emissions from electricity were not considered in this inventory.

Nitrous oxide (N_2O) is a potent GHG produced in the soil predominantly by the microbial processes of nitrification (ammonia oxidation) and denitrification (nitrate reduction) (Smith et al., 2003). These microbial processes are dependent on the availability of carbon, inorganic nitrogen, and oxygen in the soil, which in turn is affected by soil moisture, porosity, and aggregate structure (Robertson and Groffman, 2007). Management practices that influence emissions of N_2O from soils in kiwifruit orchards include the application of fertilizer N, residue management, and irrigation. We considered N_2O-emissions from soils linked to the application of inorganic fertilizer containing N, organic fertilizer (e.g., animal manure, compost), and crop residues. Nitrogen from pruned shoots and lost leaves was assumed to equal 70 kg N ha^{-1} y^{-1} in all orchards (Green et al., 2007). All N fertilizers were considered equal in their GHG emissions on a nitrogen mass (Intergovernmental Panel on Climate Change IPCC, 2007). Table 3 lists the assumed nitrogen contents of the fertilizers applied. Emissions of N_2O linked to nitrogen fertilization can occur through direct and indirect pathways. Direct emissions of N_2O result directly from the fertilized soil. Indirect emissions of N_2O are produced beyond the system's boundary, for example, the N_2O emitted from receiving water bodies or soils following nitrate leaching or runoff, and from atmospheric deposition in which soils emit ammonia (NH_3) and oxides of nitrogen (NO_x) that react to form nitrous oxide in the atmosphere (Intergovernmental Panel on Climate Change IPCC, 2007). The direct global warming potential of N_2O was assumed

Table 2
Overview of the annual frequency of management practices for organic (BIO GRO) and integrated production of kiwifruit in the Bay of Plenty for the two kiwifruit cultivars, 'Hayward' (Green) and 'Hort16A' (Gold). The data are based on a survey of 40 representative orchards. The numbers in brackets represent one standard deviation.

Management practice	Integrated		Organic	
Cultivar	Gold	Green	Gold	Green
Number of orchards	10	10	10	10
Mowing	6 (±3)	5 (±5)	2 (±2)	2 (±1)
Spraying	9 (±4)	9 (±4)	5 (±3)	8 (±3)
Mulching	2 (±0)	2 (±0)	1 (±1)	1 (±1)
Ground fertilization	1 (±1)	1 (±1)	1 (±1)	1 (±1)
Fertilization	4 (±1)	2 (±1)	1 (±1)	1 (±1)

Table 3
Amount of fertilizer needed to add one kg of nitrogen.

Fertilizer	kg fertilizer kg^{-1} N	Reference
50:50 Chicken manure: compost	47.34[a]	http://www.ecochem.com/t_manure_fert.html
CAN	3.77	(Zonderland-Thomassen et al., 2011)
DAP	5.56	(UNIDO/IFDC, 1998)
UAN	3.13	(UNIDO/IFDC, 1998)
Fishmeal	76.92[a]	http://www.ecochem.com/t_manure_fert.html
Vermicast	76.92[a]	http://www.ecochem.com/t_manure_fert.html

[a] Assuming a dry matter content of the fertilizer of 65% (Barber and Rothmann, 2008 – unpublished data).

to be 298 (Intergovernmental Panel on Climate Change IPCC, 2007). We used the same emission factors as Barber (2010), which are listed in Table 4.

2.3. Calculation of the eco-efficiency of kiwifruit production

Eco-efficiency indicators for any kind of economic activity, sector or region use data from both environmental and financial accounting systems. Eco-efficiency is defined as:

$$\text{Eco}-\text{efficiency}=\text{Economic performance}/\text{Environmental impact}.$$

This provides a ratio of the net value-added per unit of environmental impact. The higher the indicator value, the higher is the financial performance per unit of environmental burden. Data from ecological and financial accounting need to be derived from the same data set. Our data set was based on our survey of 40 kiwifruit orchards. We focused on a single environmental impact, namely greenhouse gas (GHG) emissions and quantified the environmental performance of a kiwifruit orchard as GHG emissions per ha. Considering more than one environmental issue in an eco-efficiency analysis is possible, but requires the normalization of the different environmental impact categories because of the differences in units (Kicherer et al., 2007). In contrast to the calculation of the carbon footprint of kiwifruit production for the orchard phase, we here only considered the GHG emissions directly associated with the orchard phase for the calculation of the eco-efficiency ratio. This means that all GHG emissions related to the background system of kiwifruit production, which were not directly emitted at the orchard, were excluded. This procedure ensures that double-accounting of environmental impacts is avoided (Müller and Sturm, 2001). Generally, the economic performance in an eco-efficiency analysis can be quantified in monetary units as sales or as 'value added', which is sales minus costs of goods and services. We used the latter, and normalized the indicator to a defined area of the orchard (ha). It was defined on an area basis as NZD net profit per kg CO_2e. About 90% of kiwifruit produced in New Zealand are exported. New Zealand has a single-desk export arrangement for kiwifruit meaning that all kiwifruit exported outside of Australasia are sold through a single buyer, Zespri. Sale prices for kiwifruit of export quality are dictated by global demands and trade barriers, and are the same for all growers. This means that the numerator 'value-added' is referring to the processes in the orchard.

2.4. Statistical analysis

The results of the GHG emission assessments were analysed with a two-way ANOVA with the Genstat 9.1.0.150 software. The first factor was the management system, and the kiwifruit cultivar was the second factor. We interpreted the differences between averages of GHG emissions, yields, economic parameters and eco-efficiencies ratios to be significant if they were larger than their respective least significant differences (LSD) at the 95% confidence level ($P \leq 0.05$).

Table 4
Factors used for evaluating direct and indirect nitrous oxide emissions from soil (Barber, 2010).

Description	Default value
Global warming potential of nitrous oxide	298
Emission factor for direct emissions from N input to soil	0.01
Emission factor for indirect emissions from volatilising nitrogen	0.01
Emission factor for indirect emissions from leaching/runoff of nitrogen	0.025
Fraction of synthetic N fertilizer emitted as NO_x or NH_3	0.1
N input to soil that is lost through leaching and runoff	0.07

3. Results and discussion

3.1. Life-cycle assessed carbon footprints

Including yield data in the survey enabled us to compare GHG emissions per kg of kiwifruit production to GHG emissions per ha of land in kiwifruit production. With the functional unit being mass of produce, the analysis relates GHG emissions to the production of produce of a defined quality. This is the metric in which consumers and supermarket chains are interested and which might become part of a carbon footprint label. If land area were chosen as the functional unit, the goal of the assessment would be investigating the environmental impact of production on a local area, which is a concern for both growers and regulatory agencies. Other more sophisticated functional units have been proposed such as energetic or nutrient contents of the product which describe the quality of the produce in more detail (Cederberg and Mattsson, 2000). These could potentially better differentiate kiwifruit cultivars as well as between organic v. conventional management systems in particular as there might be a relation between yield and quality. However, these functional units have not been standardized to date (Schau and Fet, 2008). We restricted our analysis to the two most commonly used and easily determined functional units, mass of produce and land use.

3.1.1. Carbon footprint per area of kiwifruit production

The GHG emissions associated with the production, packaging, storage and transportation of fertilizers were the highest emissions for all kiwifruit orchards, independent of kiwifruit cultivar and management system. This was followed by GHG emissions associated with the on-farm nitrogen cycle, fuel use and pesticide production and import (Fig. 2a and b). Table 5 provides an overview of the total GHG emissions for the two kiwifruit cultivars and the two

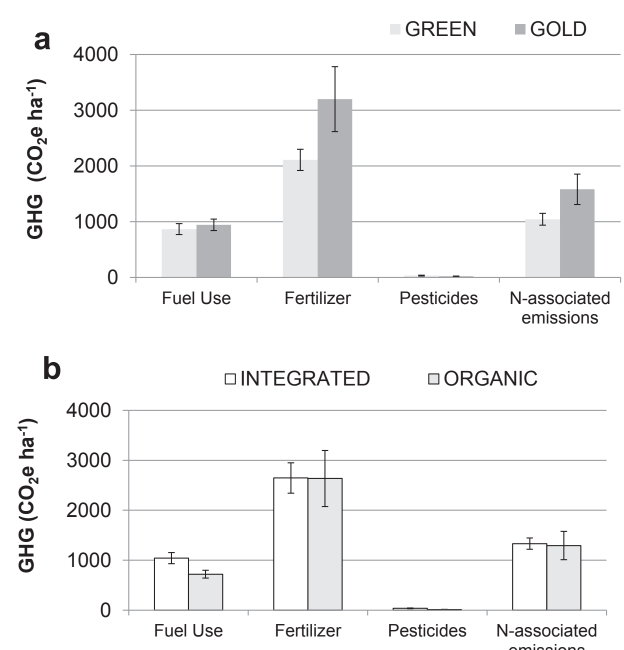

Fig. 2. (a) Average greenhouse gas (GHG) emissions for fuel consumption, fertilizer production, pesticide production and N-associated emissions for the two cultivars ('Hayward' (Green) and 'Hort16A' (Gold)) per hectare. (b) Average GHG emissions for fuel consumption, fertilizer production, pesticide production and N-associated emissions for the management practices in integrated and organic kiwifruit production systems per hectare. The bars denote the standard errors of the means.

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management systems, as well as an allocation of the total GHG emissions to the different management operations in an orchard.

3.1.1.1. *Cultivar.* 'Hort16A' fruit taste sweeter and realize a premium in the market. Recently, however, the incursion of the bacterial disease *Pseudomonas syringae* pv. *actinidiae* (Psa) in 2010 has lead to virtually all 'Hort16A' in the Bay of Plenty region being removed, as it is very susceptible to infection. The remaining rootstocks have had the more tolerant 'Gold3' cultivar grafted onto them. In other growing regions, Psa has placed a cloud over this cultivar's future. 'Hort16A' vines are more demanding of soil fertility and thus, require higher fertilizer inputs, leading to more vigorous growth of the vines. These features are reflected when comparing the GHG emissions of the two cultivars: 'Hayward' is a better prospect for reducing the GHG emissions from kiwifruit production. The total GHG emissions per area of 'Hayward' orchards tended to be lower than those per area of 'Hort16A' orchards, but these differences were not significant ($P = 0.06$) (Fig. 2a & Table 5). 'Hort16A' tended to have higher GHG emissions than 'Hayward' with terms of fertilizer inputs and the N-associated emissions ($P > 0.05$). This was attributed to higher inputs of N-fertilizers. The GHG emissions of total fuel consumption were comparable for the two cultivars. A more detailed analysis revealed that the fuel consumption was highest for mulching, and lowest for fertilization. The emissions associated with fertilizers and composts were the most important hot-spots for both cultivars.

3.1.1.2. *Management system.* Overall, the total GHG emissions of the organic and integrated management were very similar ($P > 0.05$). With regard to the GHG inventory, the largest differences between the two management systems resulted from the GHG emissions associated with total fuel use (Table 5). The emissions related to fuel use in the integrated orchards were significantly ($P < 0.05$) higher than those in the organic orchards. In integrated kiwifruit orchards, fuel use accounted for 21% of the total GHG emissions, whereas in the organic kiwifruit orchards it accounted for just 15%. The significantly higher GHG emissions from fuel use in the integrated orchards reflect the significantly higher GHG emissions of the mowing, spraying and fertilization activities in the integrated orchard system (Table 5). Integrated orchardists mowed their properties significantly more often than organic orchardists (Table 3). In general, organic orchardists do not use synthetic fertilizers but rely on natural fertilizers. Organic kiwifruit orchardists in the Bay of Plenty applied a range of organic soil amendments including compost, vermicast, poultry manure, fishmeal, and chicken manure mixed with compost at a ratio of 50:50. They also used lime, gypsum and ground phosphate rock. The fertilization practices of the organic growers led to considerable GHG emissions from the production, packaging, storage and transportation of these fertilizers, which were comparable to those from the integrated orchards related to synthetic fertilizers (Fig. 2b). In fact, the GHG emissions related to N-fertilizers and composts were the most important hot-spots for both management systems, with 78 and 85% of the total GHG emissions in the integrated and organic kiwifruit orchards, respectively (Fig. 2b; Table 5). As expected, the GHG emissions related to the production and import of pesticides were significantly ($P < 0.05$) lower in the organic orchards than in the integrated orchards. Organic orchardists do not use synthetic pesticides but, as with fertilization, they use alternative plant protection products such as copper, *Bacillus thuringiensis* (BT) and petroleum-based spraying oils. Some of these products could not be included in our estimate of the GHG emissions associated with spraying because their emission factors were not known, especially for example, BT and seaweed-based products used as biostimulants. As the amounts used were negligible, the related error was thought to be insignificant. Anyway, for both production systems, the GHG emissions related to pesticides were insignificant. They were order of two magnitudes lower than the GHG emissions associated with fertilizer production (Table 5) and accounted for 1 and 0.3% of the total GHG emissions in the integrated and organic kiwifruit orchards, respectively.

3.1.2. *Carbon footprint per kg of export kiwifruit*

Two of the 40 orchards surveyed had only recently been established and did not produce any export quality kiwifruit during the year of the survey. Both orchards were under integrated

Table 5

Average greenhouse gas (GHG) emissions (±standard error of the mean) from kiwifruit production in New Zealand for different cultivars ('Hayward' (Green) and 'Hort16A' (Gold)) and management systems (integrated, organic BIO GRO). GHG emissions are referred to area (ha) and mass of export kiwifruit (kg). Data are based on a survey with 40 orchards in a completely randomized block design[a].

GHG emissions	Gold	Green	Integrated	Organic
Emissions (kg CO_2e ha^{-1}) from				
Total fuel use	896 (±111)a[b]	867 (±100)a	1043 (±115)b	720 (±81)c
Fuel use linked to Mowing	173 (±38)a	171 (±37)a	238 (±45)b	106 (±17)c
Spraying	269 (±35)a	356 (±37)a	396 (±33)b	228 (±32)c
Mulching	432 (±60)a	318 (±54)a	379 (±66)b	371 (±52)b
Fertilization	22 (±5)a	22 (±5)a	29 (±5)b	14 (±4)c
Fertilizer use	2881 (±582)a	2005 (±217.6)a	2514 (±323)b	2372 (±549)b
Pesticide use	20 (±3)a	33 (±7)a	39 (±7)b	15 (±3)c
N-associated emissions	1582 (±280)a	1043(±108)a	1332 (±116)b	1293 (±290)b
Sum of all GHG emissions	5379 (±894)a	3948 (±325)a	4927 (±454)b	4400 (±863)b
Emissions (kg CO_2e kg^{-1}) from				
Total fuel use	0.037 (±0.006)a	0.028 (±0.003)a	0.0.30 (±0.004)b	0.034 (±0.006)b
Fuel use linked to Mowing	0.006 (±0.001)a	0.006 (±0.001)a	0.008 (±0.002)b	0.005 (±0.001)b
Spraying	0.01 (±0.001)a	0.01 (±0.001)a	0.001 (±0.001)b	0.010 (±0.001)b
Mulching	0.019 (±0.004)a	0.011 (±0.002)a	0.012 (±0.002)b	0.019 (±0.004)b
Fertilization	0.001 (±0.000)a	0.001 (±0.000)a	0.001 (±0.000)b	0.001 (±0.000)b
Fertilizer use	0.117 (±0.035)a	0.069 (±0.008)a	0.074 (±0.011)b	0.110 (±0.033)b
Pesticide use	0.0007 (±0.000)a	0.001 (±0.000)a	0.0013 (±0.00)b	0.0006 (±0.00)c
N-associated emissions	0.065 (±0.019)a	0.036 (±0.004)a	0.039 (±0.004)b	0.061 (±0.018)b
Sum of all GHG emissions[a]	0.217 (±0.058)a	0.135 (±0.013)a	0.146 (±0.017)b	0.204 (±0.055)b

[a] Two orchards under integrated management were excluded from the analysis for the calculation of the GHGs per kg produced kiwifruit because they did not produce export kiwifruit in the year of the survey. One of them grew 'Hayward' and the other 'Hort16A' kiwifruit.

[b] Figures in the same row within the factor management or cultivar followed by different letters are significantly different ($P \leq 0.05$).

management. One of them grew 'Hort16A' and the other one 'Hayward'. These two orchards were excluded from the following analysis.

3.1.2.1. Cultivar. The average yield of the 'Hort16A' orchards was 31.6 (±3.0) t ha^{-1}, while the 'Hayward' orchards' yield averaged 30.1 (±1.5) t ha^{-1}. The yields were comparable ($P > 0.05$) for the orchards included in the survey for 2009/2010. The GHG emissions per kg of kiwifruit were comparable ($P > 0.05$) for the two cultivars. This result was very similar to the GHG emissions per ha for the two cultivars (Fig. 3a).

When the focus of analysis is on the environmental impact per unit area, then the functional unit per area production is more appropriate than a mass-related functional unit. In this study, changing the functional unit did not change the overall result for the comparison of the two kiwifruit cultivars; this can be explained by the very similar yields for the two cultivars in the year of the survey. It has to be noted that the yields in the year of the survey were not typical. The average five-year (2007–2011) yield for the same orchards was 36.7 (±1.5) t ha^{-1} for the 'Hort16A' orchards, significantly ($P < 0.05$) higher than the average five-year 'Hayward' orchard yield, which was 31.6 (±0.9) t ha^{-1}. 'Hort16A' kiwifruit production was associated with slightly higher GHG emissions than the production of 'Hayward' kiwifruit for both functional units. The GHG emissions were governed by the fertilizer input. To reduce the environmental impact of 'Hort16A' kiwifruit production, growers need to optimize the nutrient cycle in the orchards, and improve the nutrient use efficiency of the kiwifruit vines. More accurate data for estimating GHG emissions related to nitrogen in the orchard phase are required to reduce uncertainties in the LCI phase.

3.1.2.2. Management system. Based on the data of our survey, we found that the kiwifruit yield in the Bay of Plenty was significantly ($P < 0.05$) lower under organic than under integrated management. The average yield of the integrated orchards was 36 (±2.5) t ha^{-1}, while the organic orchards' yield averaged 26.2 (±1.6) t ha^{-1}. Table 5 includes a comparison of the GHG emission for the different management activities per kg of kiwifruit. The GHG emissions per kg of organically produced kiwifruit tended to be higher than those under an integrated management system but these differences were not significant ($P > 0.05$; Fig. 3b).

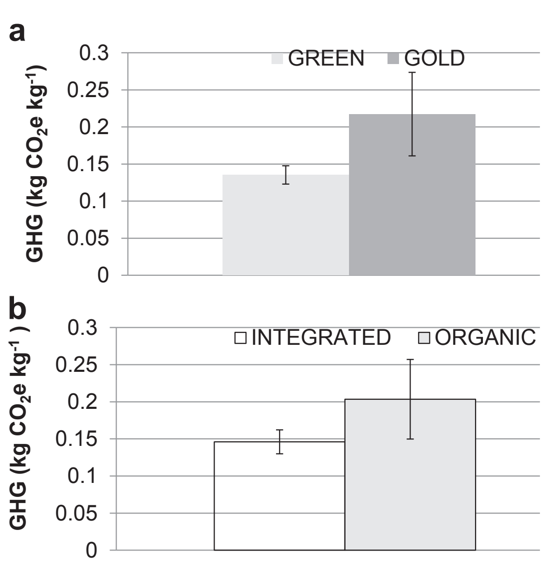

Fig. 3. (a) Average greenhouse gas (GHG) emissions per kg kiwifruit in the orchard phase for the two cultivars ('Hayward' (Green) and 'Hort16A' (Gold)). (b) Average GHG emissions per kg kiwifruit for the management practices in integrated and organic kiwifruit production systems. The bars denote the standard errors of the means.

The choice of the functional unit for the analysis affected the comparison of the two management systems, but only when considering specific management activities in the orchards (Table 5): Organic production had a significantly more favourable outcome than integrated production with respect to GHG emissions related to total fuel use and pesticide use, but only when the analysis was area-based. The benefits of organic production were reduced when the lower yields were taken into consideration and applying the mass-related functional unit. This underscores the need for organic low input systems to increase yields per hectare. A recent study applied a meta-analysis of available information and concluded that, on average, organic yields are 25% lower than those achieved in conventional agriculture. However, it also showed that these yield gaps varied significantly between crops. Interestingly, Seufert et al. (2012) showed that organic fruit production had just 3% lower yields on average than conventional fruit production, based on studies with apples and strawberries produced in Switzerland, Canada and the USA. For kiwifruit production in New Zealand, this yield gap between organic and conventional production systems seems to be larger than 3%. A recent study comparing nutrient budgets between organic and conventional kiwifruit systems in the Bay of Plenty showed that yields in organic orchards were significantly lower than in integrated orchards even though nutrient inputs were larger than the nutrient removals for both systems (Carey et al., 2009). These differences were mainly attributed to the use of the plant growth stimulator hydrogen cyanamide to synchronize the budbreak and flowering in integrated production systems. In addition, in our study, the rate of kiwifruit rejection caused by small sized fruit was considerably higher for organic than for integrated orchards. This highlights also that the availability, rather than the total amount of nutrients in the soil, is an issue in organic systems (Berry et al., 2002). The mineralization rates of organic soil amendments need to be better estimated and controlled to ensure timely delivery of plant-available nitrogen to the kiwifruit vines. Deliberately including legumes in the sward to fix nitrogen from air could also reduce GHG emissions provided the soil nutrient storage was effectively managed. Another solution might be processing organic compost by anaerobic digestion, which would allow the timely delivery of readily plant-available nitrogen in the form of ammonium to the vines instead of organically bound nitrogen and would also improve the overall energy balance of orchards by producing biogas methane that could be used as fuel or for heating (Tuomisto et al., 2012).

Common perception is that organic farming is associated with lower environmental impacts than conventional farming (Gracia and de Magistris, 2008). In a global meta-analysis study Mondelaers et al. (2009) found out that the GHG emissions of organic agriculture were generally lower than those of conventional agriculture when the emissions were expressed per unit area but comparable when emissions were expressed per mass of produce. Our measurements, which only considered GHG emissions as environmental impact, do not support these findings. Irrespective of the functional unit selected, the GHG emissions of organic and integrated kiwifruit orchards were comparable, and tended to be even larger for the organic than the integrated orchards when the functional unit was mass of export kiwifruit. Tuomisto et al. (2012) reported, based on a meta-analysis of 71 European studies that the production of some organic products had lower GHG emissions than conventional products but for some other products, e.g. milk, cereals and pork this response ratio impact of organic farming/impact of conventional farming was reversed. The overall median response ratio for GHG emissions was zero. They stressed that higher GHG emissions in organic than conventional management systems was often associated with the functional unit mass of produce. This highlights the need for organic low input systems to increase productivity and indicates that opportunity costs of land use need to be considered in the debate about the environmental impacts of conventional and organic agricultural management systems.

3.2. Eco-efficiency analysis

Our survey was not limited to management activities in the orchards but also considered the economic side of kiwifruit production, including costs and income per ha of production. Based on these data, we estimated the net profit per ha of each orchard and used this as financial measure for assessing the eco-efficiency of kiwifruit production under organic and integrated management, as well as for the two cultivars considered in this study. Three of the 40 orchards included in this study made a loss during 2010.

3.2.1. Cultivar

'Hort16A' kiwifruit realised significantly ($P < 0.05$) higher prices in the marketplace than 'Hayward' kiwifruit. This was reflected in the significantly ($P < 0.05$) larger net profit per area of 'Hort16A' kiwifruit production (33,526 ± 6651 NZD) than for 'Hayward' kiwifruit production (12,702 ± 4021). 'Hort16A' yielded a significantly higher net profit/ha despite the fact that growing 'Hort16A' was associated with higher agrichemical inputs and higher costs ($P < 0.05$) than growing 'Hayward' kiwifruit. The estimated eco-efficiency expressed as NZD net profit/ha per kg of GHG emissions/ha tended to be higher for 'Hort16A' than for 'Hayward' kiwifruit (Table 6). However, the difference between the two cultivars was not significant ($P = 0.103$) (Fig. 4a). This was attributed to the unexpected similarity of the yields of 'Hort16A' and 'Hayward' kiwifruit of the orchards participating in our survey in the year of the survey. It remained unclear why the yields of the year under investigation were relatively anomalous. In order to overcome some of the annual yield and price variability clouding the usefulness of the eco-efficiency indicator, average yield and profitability data per hectare of the same orchard stage could be used. This approach has been proposed for the ecological footprint analysis (Cerutti et al., 2013). However, these data were not captured in our survey. Our results also highlight that achieving high yields for an entire orchard over a period of years requires the skilful allocation of resources to orchard blocks of different cultivars and at various productivity stages.

3.2.2. Management system

Fruit produced under organic management generally yield premium prices in the marketplace. In the year of the investigation, our growers sold 1 kg of organically grown kiwifruit for a

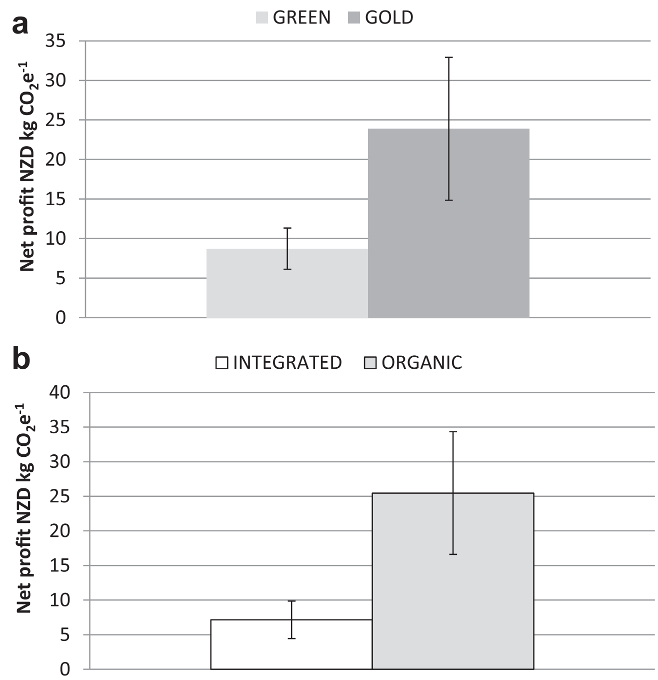

Fig. 4. (a) Average NZD profit/ha per kg greenhouse gas emissions (CO_2e) for 'Hayward' (Green) and 'Hort16A' (Gold) production. (b) Average NZD profit/ha per kg greenhouse gas emissions (CO_2e) for kiwifruit grown under organic and integrated management systems. The bars denote the standard errors of the means.

significantly ($P < 0.05$) higher price than 1 kg of kiwifruit grown in an integrated orchard. This was reflected in the larger net profit per area for an average organic (30,974 ± 5560 NZD) than for an average integrated orchard (15,253 ± 5864). This difference was significant ($P < 0.05$) even though the premium price per kg fruit does not directly translate to the same premium per ha, because of the lower yields in organic orchards (Table 6). Based on the orchards participating in our survey, organic orchards were substantially outperforming integrated kiwifruit production in terms of net profit, in spite of similar production costs. The costs of organic and integrated kiwifruit production were similar because of the relatively high costs of pest and disease control and soil amendments in organic orchards, despite organic orchards being lower input systems (Campbell et al., 1997). Finally, the estimated eco-efficiency expressed as NZD net profit/ha per kg GHG emissions/ha was significantly ($P < 0.05$) different between the two management systems (Fig. 4b). Organic management systems realised 25.5 (±8.9) NZD net profit per kg of GHGs emitted, and this compared with 7.2 (±2.7) NZD net profit per kg GHG emissions/ha in

Table 6
Average greenhouse gas (GHG) emissions (and standard error of the mean (sterr)) from kiwifruit production in New Zealand for different cultivars ('Hayward' (Green) and 'Hort16A' (Gold)) and management systems (integrated, organic BIO GRO). GHG emissions, economic data and eco-efficiency are normalized by the area of production (ha). Data are based on a survey with 40 orchards in a completely randomized block design.

		Integrated		Organic		Green		Gold	
		Mean	Sterr	Mean	Sterr	Mean	Sterr	Mean	Sterr
Economic data	Income NZD ha^{-1}	76043a	8666	84567a	7841	60768b	4987	99842c	8570
	Total costs NZD ha^{-1}	60790a	4446	53592a	2338	48066b	1899	66317c	3771
	Net profit NZD ha^{-1}a	15253a	5864	30974b	5560	12702c	4021	33526d	6651
	Yield t/ha	36a	2.5	26.2b	1.6	30.1c	1.5	31.6c	3.0
GHG emissions	Fuel use related kg CO_2e ha^{-1}	1043a	115	720b	81	867c	101	896c	111
	N-associated kg CO_2e ha^{-1}	1332a	116	1293a	290	1043b	108	1582b	280
	Total kg CO_2e ha^{-1}	2375a	172	2013a	329	1910b	158	2478b	328
Eco-efficiency	Net profit NZD kg CO_2e^{-1}	7.16a	2.70	25.46b	8.86	8.74c	2.61	23.88c	9.04

Figures in the same row with management or cultivar followed by different letters are significantly different ($P \leq 0.05$).

integrated kiwifruit orchards (Table 6). However, if yield (kg ha^{-1}) was used as numerator for calculating the eco-efficiency, then the average organic orchard still tended to have a higher eco-efficiency than the average integrated orchard, but this difference was not significant ($P > 0.05$). This highlights that the yield gap between organic and integrated orchards system needs to be narrowed. Kulak et al. (2013) called for 'sustainable intensification'. It also stresses the importance of premium prices and the market value of a product for the eco-efficiency of orchard systems. As others already noted revenue-based indicators are volatile to prices and are restricted to comparing systems with identical market situations (Cerutti et al., 2011). We successfully applied the indictor eco-efficiency to differentiate between various kiwifruit production and commercialisation systems in a single region. It could also be used to compare the sustainability of orchard production systems in different regions, such as, for example, kiwifruit production in the Bay of Plenty region and Hawke's Bay region. In this case, the eco-efficiency indicator would integrate the impact of pedo-climatic conditions on orchard management strategies and in return on the environmental and economic performance of the orchards. Thus, eco-efficiency could also be a useful tool to inform policy to redirect resources to areas of greater eco-efficiency. In general, more research is needed to increase our understanding of the trade-offs between environmental impacts and the resource efficiency and productivity of orchards. While the eco-efficiency concept has been applied to cropping systems (Kulak et al., 2013), dairying (Basset-Mens et al., 2009; Meul et al., 2007b), sugar beet production (Wieβner et al., 2010) and apple orchards (Mouron et al., 2006) in the past, our study is, to the best of our knowledge, the first application of the eco-efficiency concept to kiwifruit orchards.

4. Conclusions

In this study, we found that the carbon footprints of organic and integrated kiwifruit production at the farm gate were comparable. Our analysis revealed fertilizer use and N-associated emissions as the hot spots for GHG emissions from kiwifruit orchards in the main kiwifruit growing region in New Zealand. Significant reductions in the carbon footprints could be achieved by changes in the background system, such as different transport routes and different product choices. In addition, kiwifruit growers could reduce their carbon footprints by improving the nitrogen-use efficiency of the fertilizers used in orchards. This could be achieved by more accurately adjusting fertilization to plant needs by monitoring and accounting for plant-available nitrogen in the soil.

While the overall results of the LCA did not change whether the functional unit was area or mass based, the relative positions of the carbon footprints shifted between the two management systems. The area-based carbon footprint of organic kiwifruit production was more favourable than the carbon footprint of integrated production. But using the mass-based carbon footprint, integrated management had a slightly more positive outcome than organic management. This underscores the problem of the significantly lower yields in the organic kiwifruit orchards. This yield gap, which essentially is the difference between actual yields and the yields that are possible with known technologies and best practices, is a problem for organic production systems in general, and needs to be addressed. Solutions might include the development of production systems that combine techniques from both organic and conventional systems leading to the highest possible yields with the lowest negative environmental impacts. Our study shows that applying different functional units in LCA is a useful approach to identify the optimum balance of external inputs, environmental trade-offs and yields between various production systems.

Taking into account the economic performance of the orchards, the kiwifruit orchards under organic management had the highest average eco-efficiency in this study. Organic kiwifruit yielded premium prices in the market, which led to a higher net added value, in spite of lower yields and the comparable greenhouse gas emissions from fuel use and N-related emissions for the two management systems. These results highlight that eco-efficiency is closely related to market prices and economic outcomes. It also emphasizes the market power of consumers' purchasing decisions for promoting sustainable agricultural production systems. The volatility of commodity markets is an issue, even though linking information on the environmental performance of kiwifruit orchards to their financial performance could help orchardists to make informed decisions about which cultivars to grow under which management systems, to optimize the sustainability of their orchard production system and to provide them with environmental performance credentials in relation to GHGs.

Future studies that extend this analysis by taking into account other environmental impacts of production systems are needed. This approach might then help agricultural production systems to become more environmentally responsible and at the same time more profitable. In future studies, social aspects should also be taken into consideration.

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