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Towards use of life cycle–based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand

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Abstract

Purpose A life cycle assessment (LCA) study was undertaken for the orchard stage of the NZ avocado value chain, to guide the development of indicators for facilitating continuous improvement in its environmental profile.

Methods The functional unit (FU) was 1 kg Hass avocados produced in NZ, up to the orchard gate. The baseline model assessed avocados produced in fully productive orchards, using input data collected from 49 orchards across 281 ha in the three main avocado growing regions of New Zealand. In addition, the non-productive and low production years of avocado orchards were assessed using data from four newly established avocado operations spread across 489 ha. Climate change, eutrophication, water use, freshwater ecotoxicity and terrestrial ecotoxicity results were calculated for each orchard. Finally, national scores were calculated for each impact category from the weighted averages of the individual orchard results in the baseline sample of the three studied regions.

Results There was significant variability between orchards in different input quantities, as well as impact scores. The impact assessment results showed that fuel use and fertiliser/soil conditioner production and use on orchard were consistently the main hotspots for all impact categories except water use, where impacts were generally dominated by indirect water use (irrespective of whether the orchards were irrigated or not). When considering the entire orchard lifespan, the commercially productive stage of the orchard life contributed the most to all impact category results. However, the impacts associated with 1 kg avocados, when allocated based on the total impacts across the orchard lifespan, were 13–26% higher than the baseline results which considered only the commercially productive years of the orchard life.

Conclusion The study identified the priority areas for focussed improvement efforts (in particular, fertiliser and fuel use for all impact categories, and agrichemical use for the ecotoxicity impacts). Second, the regional- and national-level impact scores obtained in this study can be used as benchmarks in indicator development to show growers their relative ranking in terms of environmental performance. When using the indicators and benchmarks in a monitoring scheme, consideration should be given to developing separate benchmarks (using area-based functional units) for young orchards. It will also be necessary to develop a better understanding of the reasons for the variability in inputs and impacts so that benchmarks can be tailored to account fairly and equitably for the variability between orchards and regions.

Keywords Life cycle assessment · Food production · Avocados · Climate change · Green supply chain · New Zealand

1 Introduction

1.1 Avocado production in New Zealand

Food security and sustainable food systems are high on global policy agendas (United Nations Department of Economic and Social Affairs 2015; HLPE 2017, 2020; FAO and WHO 2019; FAO et al. 2023). Current conventional practices in agri-food supply chains are important driving

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factors for climate change, biodiversity loss, water scarcity and environmental ecotoxicity. It is therefore becoming increasingly important to transform agri-food value chains to make them more sustainable. This is particularly the case in New Zealand as its economy is closely linked to the effective—and continued—operation of its primary sector and is evidenced by the Zealand government providing funding and other forms of support for making the primary sector more sustainable (The Beehive 2018; MPI 2023). The primary sector is responding by increasingly addressing sustainability in its operations (Beef + Lamb NZ 2018; DairyNZ 2022; NZ Avocado 2022, 2023; NZ Wine 2022; Zespri 2022).

The largest primary industries in New Zealand have traditionally been dairy, meat and wool and forestry. However, New Zealand's $10 billion export-driven horticulture industry is now being called the 'fourth engine' of the country's primary industry sector (NZ HEA 2017; Horticulture New Zealand and Plant & Food Research, 2018, 2021; Gray 2018; Ministry for Primary Industries 2018) and also the one that has suffered and yet been resilient in the face of extreme global and national events like the COVID-19 pandemic and Cyclone Gabrielle (Apparao et al. 2023). While the kiwifruit and apple sectors have traditionally contributed the largest shares of fresh fruit exports, the avocado sector has shown steady growth over the last decade in registered growers, new orchards planted and tray volumes produced (NZ Avocado 2021). The New Zealand avocado sector has over 1800 growers, who collectively manage more than 4000 ha of planted avocados, mainly the Hass variety. Avocados are grown in the North Island, mainly in the Bay of Plenty and, to a lesser extent, Northland (Far North and Mid North, mainly Whangarei). The production volumes in the avocado-producing regions of the country are shown in Table 1. The avocado sector's total value increased from $67.9 million in 2011 to $233.6 million in 2021. This growth has been fuelled by the growing export demand—the sector's export value grew from $45.5 million in 2011 to nearly $168 million in 2021 (year ended June).

Given the NZ avocado sector's rapid growth and increasing focus on sustainability (NZ Avocado 2018, 2022), an LCA study was recently conducted to quantify the environmental impacts associated with growing avocados in New Zealand and identify the environmental 'hotspots', i.e. the main inputs, activities and/or stages in the productive stage that make the biggest contribution to the environmental impacts. The current paper explores the results of this study, including an orchard whole-of-life perspective, and discusses the implications for developing indicators to drive continuous improvement in the New Zealand avocado sector.

1.2 Avocado LCA research

Thirteen avocado-related LCA resources were identified in the literature (SI Table 1). Most of them are peer-reviewed journal articles; the others include public disclosure statements, a student report and two industry reports. Five of the studies considered several fruits and vegetables and did not provide much detailed information about avocados specifically. Some studies included just one or two impact categories, and others considered multiple impacts; however, all the studies addressed climate change/GHG emissions.

The system boundaries varied considerably across the studies. While the orchard stage was considered in all the studies, some of them modelled impacts 'from cradle to farm gate' (Bell et al. 2018; Graefe et al. 2013), while others looked at impacts 'from cradle to point-of-sale' (Stoessel et al. 2012), and 'from cradle to grave' (Frankowska et al. 2019). The term 'cradle' was found to vary amongst studies with respect to the nursery inputs into the orchard. Esteve-Llorens et al. (2022) included the productive (orchard) stage and post-harvest processing (packaging and transport to the port of dispatch) but excluded the nursery stage, stating its impacts would be negligible in the overall avocado life cycle. However, Bell et al. (2018) noted this as a limitation in their own study, while Frankowska et al. (2019) and Solarte-Toro et al. (2022) included all nursery operations and inputs within their system boundaries. A similar trend was noted when the literature search was extended to other perennial fruits like kiwifruit and apples, and the wider literature on system boundaries for other fruit production systems. Many LCA practitioners, while noting that the importance of the nursery stage in LCA studies is often underestimated or even not acknowledged, advocate including it (Bessou et al. 2013; Cerutti et al. 2014). As some authors note, plant nurseries can be highly environmentally demanding, in terms of

Table 1 Annual volumes produced by region in the period of 2018 to 2021, volume in 5.5 kg tray equivalents ('000s) (source: NZ Avocado 2020)

Region	2020–2021		2019–2020		2018–2019		2017–2018	
	Volume	Ha	Volume	Ha	Volume	Ha	Volume	Ha
Far North	764	866	717	548	729	534	711	555
Mid North	1072	810	494	833	545	813	397	817
Bay of Plenty	2835	2198	2322	2294	1639	2307	1055	2319
Rest of NZ	140	271	85	262	66	141	72	149
Total	4811	4145	3617	3937	2979	3795	2235	3839

resources, structures and technology (Cerutti et al. 2014; Nicese and Lazzerini 2012) and this applies to ornamental plants as well as perennials like walnut trees (Cambria and Pierangeli 2012; Lazzerini et al. 2014). However, often there is a lack of reliable data for this stage (Graefe et al. 2013; Vatsanidou et al. 2020).

Most published fruit-related LCA studies consider only 1 year of orchard production, when the orchard is mature enough for commercial production (Bessou et al. 2013). However, yields are variable across the lifespan of the orchard and this variability can have a direct impact on the results (Cerutti et al. 2011, 2014; Bessou et al. 2013; Alaphilippe et al. 2016; Svanes and Johnsen 2019). This has been illustrated in the production of different perennial crops like peaches (Vinyes et al. 2015), apples (Alaphilippe et al. 2016; Goossens et al. 2017) and Brazilian cashews (Brito de Figueirêdo et al. 2016) amongst others. Only two avocado LCA studies considered the full orchard lifespan instead of only the fully productive years. Solarte-Toro et al. (2022) reported results for the first 11 years of the orchard until it reached peak production. And D'Abbadie and Akbari (2023) considered the first 15 years of the orchard and presented their results for the orchard stage as an average value over the 15 years as well as the targeted result for year 7 (i.e. when the orchard reached peak commercial production). Neither of the studies mention the low production years towards the end of the orchard life.

A number of limitations are noted in the LCA studies. The most common one is data uncertainty due to secondary sources of data; in particular, a number of studies mention the use of proxy data related to farm operations conducted by third-party contractors as well as used as a replacement for missing primary data (Bell et al. 2018; Frankowska et al. 2019; Hadijan et al. 2019). Also, Stoessel et al. (2012) pointed out that food losses (not included in their study) may in reality be significant. The potential for carbon sequestration by avocado trees was noted by Graefe et al. (2013). Sample size is also an issue; Esteve-Llorens et al. (2022), for example, assessed three avocado producers but noted that the study could be considered to be broadly representative of Peru's avocado production due to the large production areas of the considered producers.

While there are some LCA studies of the NZ horticultural sector, most are carbon and water footprints exclusively (Hume et al. 2010; McLaren et al. 2009, 2010; Mithraratne et al. 2010; Herath 2013; Herath et al. 2013; Robertson et al. 2014; Müller et al. 2015). More detailed LCA studies exist for apples (Milà I Canals et al. 2006) and wine (Barry 2011). McLaren et al. (2021a) recently updated the previous carbon footprint studies on kiwifruit, apples and wine. And a preliminary overview of the results of this current avocado LCA study was presented at the International LCA Food Conference in Peru (Majumdar et al. 2022).

The novelty of this study lies in the fact that there has been very little LCA research on avocado production, and no research on NZ avocados has been conducted yet (as noted in Sect. 1.2). Furthermore, it extends beyond the LCA itself to also evaluate indicator and benchmark development to support continuous environmental improvement in the sector using key factors identified in the LCA. The results of this study will be useful to a target audience that is interested in the quantified environmental impacts of avocado production, in general, and in NZ, in particular. The study could help the industry association plan its environmental improvement strategy going forward and could help individual growers as well.

2 Methodology

2.1 Goal and scope

The function of the orchard is to produce fresh avocados in New Zealand, which can then be consumed locally or exported. The functional unit (FU) chosen for this study was therefore 1 kg Hass avocados, at the farm gate. Data were collected for a reference flow of 1 ha of worked avocado orchard, and this was used to calculate the results for 1 kg avocados. The system boundary for the baseline model extended from the cradle (activities including the production and transport of materials and energy, upstream from the core agricultural activities) to the orchard gate. The nursery stage was excluded from the analysis due to lack of data. Capital equipment production and maintenance was excluded as recommended by the EPD International (2019) guidelines (and common practice in process-based LCA; Hauschild et al. 2018, p. 1073). However, the infrastructure for orchard establishment (wooden posts, steel wire, water tanks, etc.) was modelled in the orchard whole-of-life scenario. Also, following the EPD International (2019) cut-off criteria guidelines, this study excluded all elementary flows to and from the system that contributed $< 1\%$ of the final result to any impact category (e.g. packaging for fertilisers and agrichemicals, kelp fertilisers, plant growth hormones). In addition, any change in soil carbon due to land use change was outside the scope of this study. Primary data was used for input types and quantities to all foreground processes, while secondary data (ecoinvent datasets) were used for background processes (e.g. extraction of raw materials, production of fertilisers), which represent average technology used globally/regionally. The New Zealand–specific electricity grid mix was used for all electricity inputs on farm.

2.2 Impact categories and assessment methods

The following impact categories used in this study were identified in an earlier materiality assessment undertaken by NZ Avocado: climate change, eutrophication, water use and ecotoxicity (freshwater and terrestrial). As per the EPD International (2023) guidelines, the following methods were used:

- Climate change: global warming potential (kg CO_2 eq.). GWP100, CML 2001 baseline (excluding biogenic carbon), version: January 2016
- Eutrophication: eutrophication potential (EP), CML 2001 baseline (fate not included)
- Water use: water deprivation potential, Available Water Remaining (AWARE) method
- Freshwater ecotoxicity: USEtox 2.12 (recommended and interim factors[1])
- Terrestrial ecotoxicity: ReCiPe 2016 (V1.1) (H)

For eutrophication, although ReCiPe 2016 provides updated characterisation factors based on a global fate model, its fate modelling assumes that P is a limiting factor in freshwater environments. But, freshwater environments in New Zealand are often limited by both N and P, and therefore, there is an inherent methodological uncertainty/limitation when using ReCiPe 2016 for New Zealand conditions (Payen and Ledgard 2017). Therefore, the CML 2001 method was used in this study; it assumes 100% of the emissions of both N and P contributes to eutrophication impacts and therefore provides a 'worst-case' scenario.

For water use, AWARE characterisation factors (CFs) are provided on a national, sub-national and watershed levels, and for agricultural, non-agricultural and unspecified water uses. While watershed-level factors provide the highest level of resolution, it was not possible within the scope of this study to determine the exact watersheds from which each orchard sourced its water for direct on-orchard use. Therefore, for this study, the sub-national agricultural CFs were used for direct water use on orchards (irrigation, spraying, fertigation and frost protection): one for Northland (the Far North and the Mid North) and one for the Bay of Plenty. The relevant country-level unspecified values were used for indirect (upstream) water use (e.g. production and manufacture of inputs like agrichemicals and fertilisers).

For toxicity assessment, USEtox 2.12 was chosen as it is preferred by the wider scientific community (Hauschild et al. 2011). As USEtox only assesses freshwater ecotoxicity, ReCiPe 2016 (V1.1) (H) was used to model terrestrial ecotoxicity impacts; this method includes emission flows for most of the pesticides used in the avocado orchards. For the fate of pesticides, it was assumed that 100% of the active ingredient (AI) emissions from all applied pesticides went to agricultural soil (following EPD International 2019, Sect. 4.10.2.6, p. 16), and as discussed in Fantke (2019), Nemecek and Schnetzer (2012), Christel et al. (2014) and Nemecek et al. (2020). However, as current life cycle impact assessment (LCIA) methods do not account for impacts to on-field agricultural soil (Rosenbaum et al. 2015; Notarnicola et al. 2017), only their impacts outside of the agricultural soil compartment were assessed in the study.

2.3 Sampling strategy and data collection

2.3.1 Baseline model

A stratified sampling strategy was used to select orchards for the study. Firstly, random sampling was carried out for orchards in each of New Zealand's three main avocado-producing regions: the Bay of Plenty, Mid North and Far North. Only orchards with production data for a minimum of 2 years (2018–2019 and 2019–2020) were considered, and most orchards had at least 4-year data.

The selected orchards were further categorised by production practices (best practice, good practice and standard practice) and by orchard area (big (> 5 ha), medium (2.0–5 ha) and small (< 2 ha)). The orchards identified for the baseline model spanned a cumulative area of 281 ha. The production practice categories were determined by the yield of each orchard (kg/hectare, averaged for the years 2016–2020) and its irregular bearing index (IBI). Irregular or alternate bearing is the tendency of a perennial fruit tree to have an 'On' year of heavy fruiting, followed by an 'Off' year of a very light crop (Lovatt 2010; Sharma et al. 2019). The IBI of fruit trees was calculated using the following formula (Rosenstock et al. 2010):

$$I = \sum_{t=2}^{n} \frac{\left|y_t - y_{t-1}\right| / y_t + y_{t-1}}{n-1}$$

where I is equal to the sum of the absolute value of the difference in yields (y) between two consecutive years (t and $t-1$), divided by the sum of the yields in the same 2 years, and then divided by the number of years minus 1 (n). For the NZ avocado sector, this value was calculated for each year between 2016 and 2020.

Questionnaires were sent to 108 sampled orchards (to collect orchard data for the period 1 November 2018 to 31 October 2019), with follow-up visits to clarify questions regarding the data and ensure consistency and accuracy. Of the 53 responses received, four 'supra massive'[2] orchards

[1] USEtox provides a distinction between 'recommended' and 'interim' characterisation factors, based mainly on the applicability to respective substances or on the availability/quality/reliability of input data. However, ideally, it is recommended that both be included (Life Cycle Initiative 2023).

[2] 'Supra-massive' refers to the larger-than-usual (> 50 ha) orchards that are being planted in the Far North. These orchards had been planted within 1–3 years of data collection and had very low yields at the time of data collection.

were classified as young orchards with very low yields and were excluded from the baseline sample. Thus, the final sample for the baseline model comprised 49 mature orchards across the three regions (11 in the Far North, 14 in the Mid North and 24 in the Bay of Plenty).

For the baseline model, the orchard production–based weighted average impact scores for each orchard were calculated for the three regions. The regional impact scores were weighted again, based on regional production data, to provide a national production–based weighted score for each impact category.

2.3.2 Orchard lifespan

Perennial fruit trees have much longer lifespans than field crops (10–> 50 years), depending on the fruit species. As noted in Sect. 1.2, most published fruit-related LCA studies consider only 1 year of mature orchard production and thus exclude the impacts of the unproductive years (orchard creation and destruction), and low production stages of the orchard establishment and senescence (the initial years between orchard establishment and commercial production as well as the later (low-yield) years of ageing trees). Excluding these specific stages in the orchard life cycle may lead to underestimated LCA results (Bessou et al. 2016; Brito de Figueirêdo et al. 2016; Goossens et al. 2017; Vatsanidou et al. 2020). On the other hand, including these specific stages in the orchard life misrepresents the productive stage as the LCA results will be higher due to the average annual yield being lower when calculated based on the full life cycle of the orchard. To address this aspect, Cerutti et al. (2014) recommended modelling an orchard in six life cycle stages: (1) nursery stage with sapling production,[3] (2) planting and field preparation, (3) early low-production phase as the orchard matures, (4) full production, (5) declining production due to ageing trees and (6) orchard destruction and removal/disposal of trees.

For this LCA study, the full lifespan of the avocado orchard was modelled as a separate exercise, following the modular modelling approach proposed by Bessou et al. (2013). The different orchard lifespan stages and yields are shown in Table 2; inputs for the orchard establishment stage were collected from each of the four supra-massive orchards (spread over 489 ha), and their impacts were assessed separately and then averaged. Additionally, orchard infrastructure data was collected from one of the supra-massive orchards to model the orchard creation stage; this orchard was chosen as it had relatively more infrastructure than all the other orchards in the study and so was likely to represent the most extreme scenario with respect to infrastructure. For the senescent years of the orchard life, it was assumed that the inputs and yields towards the end of orchard life would be the same as the orchard establishment. The nursery stage and orchard destruction stages were not modelled due to the lack of data.

Table 2 Stages in the orchard life and assumed yield at each stage

Stage in orchard lifespan	Orchard yield (kg/ha/year)
Year 0, orchard creation	0
Years 1–3, orchard establishment	1887[a]
Years 4–47, commercial production	14,723[b]
Years 48–50, orchard senescence	1887[a]

[a]Average yield of four supra-massive orchards in the Far North during years 1–3

[b]Average yield of baseline model orchards in the Far North

3 Inventory data

3.1 Inventory data for baseline model

3.1.1 Agrichemicals

Data on agrichemical use was obtained from the spray diaries completed by orchards as part of NZ Avocado's AvoGreen programme. The calculation and analysis of agrichemical emissions was based on the AI of the pesticide products (SI Table 2), whereas production impacts were based on the inputs for the formulated products. For insecticides, there are very limited inventory datasets available, and none was found for the AIs of insecticides used for avocado production in New Zealand. Therefore, the closest groups of chemical families related to the AIs used in New Zealand avocado production were selected and used to create an 'average insecticide production' dataset. For fungicides, five copper-based fungicides are used on avocado orchards in New Zealand (formulations of copper oxide, copper hydroxide, copper oxychloride, cuprous oxide and tribasic copper sulfate) (SI Table 3); their impacts were calculated based on the copper content as the AI. As many agrichemical products for NZ avocado growing are imported from Europe, the model assumed truck transport from a manufacturing plant to the Port of Hamburg (100 km), ocean shipping to the Port of Auckland (27,663 km), truck transport to a regional storehouse in Tauranga/Whangarei (~ 200 km) and, finally, truck transport to the orchard (100 km). As mentioned in Sect. 3.2, all pesticide AIs were modelled for 100% emission to agricultural soil.

[3] While the nursery stage is considered a separate upstream life cycle stage in some LCA studies, other studies consider it to be an extension of the orchard stage which involves growing the saplings as inputs to the orchard planting and preparation stage.

Table 3 Machinery and fuel generally used for activities on avocado orchards

On-orchard activity	Machinery (fuel used for activity)	Fuel use rates (L/h)
Mowing	Mower (petrol/diesel)	2.5
	Tractor (diesel)	8.6
Spraying pesticides (weeds)	Tractor (diesel)	2.5
Spraying pesticides (others)	Tractor and spray unit (diesel)	10.4
Spraying foliar fertilisers	Tractor (diesel)	9.6
	Cropliner (diesel)	12
Applying non-foliar fertiliser	Quad bike (also known as all-terrain vehicle or ATV) (petrol/diesel)	2.3
Chipping	Chipper (petrol/diesel)	10
Shelter belt trimming	Tractor (diesel/petrol)	11.6
Pruning	Chainsaw (petrol)	0.3
	Hydralada (petrol/diesel)	1.8
Harvesting	Hydralada (petrol)	1.7
	Hydralada (diesel)	8
Digging	Digger	9.7
Irrigation	Pump (electric/diesel)[a]	–
Other on-orchard transport	Quad bike (petrol)	2
	Tractor (diesel)	4.5
	Motorbike (petrol)	2.5
	Forklift (diesel)	3
	Forklift (LPG)	4

[a]Depends on mass flow rate of the pump, and whether the extracted water is surface or groundwater

3.1.2 Fertilisers/soil conditioners

Fertiliser and soil conditioner use data was obtained from the spray diaries completed by NZ avocado growers as part of the AvoGreen programme and was supplemented with additional data from the questionnaires filled in by the growers. Most of the products used on New Zealand avocado orchards are straight/simple fertilisers (SI Table 4). For blended and complex fertilisers, the component quantities were calculated separately and used as inputs to the orchard

Table 4 Infrastructure items/materials for orchard creation (including lifetimes)

Infrastructure category	Item/material	Lifetime of each input (years)	Quantities used across orchard lifespan (kg/ha)
Wind protection	Wooden posts	25	4000
	Plastic netting	12.5	840
	Plastic clips	12.5	91
	Steel wire	25	192
Frost control/protection	Wooden posts	25	500
	Plastic pipe (vertical)	25	185
	Plastic pipe (horizontal)	25	3440
	Sprinkler heads	25	1.5
Irrigation	Plastic pipes	25	2752
	Sprinkler heads	25	8
	Water tanks (galvanised steel)	50	20,500
	Water tanks (plastic liner)	50	3000
Protection for saplings/ younger trees	Plastic bags	50	59
Weed control	Plastic weed mats	12.5	194
Digging/forming rows	Fuel (diesel)	50	303 (L/h)

processes, using the straight fertiliser datasets (SI Table 5, Table 6). Like agrichemicals, all fertilisers were modelled to include product formulation, except for those which were entirely made of the constituent chemical.

For production-related climate change impacts, the European ecoinvent datasets were used where they were available, and otherwise, global datasets were used. However, Brentrup et al. (2018) recommended updated carbon footprint values for the production of certain commonly used fertiliser products in different regions of the world. Therefore, the ecoinvent datasets for the production of these relevant fertilisers were updated to reflect the global warming potential (GWP) values in Brentrup et al. (2018).

Transport of fertiliser products was modelled in the same way as for agrichemicals (produced in Germany and transported to NZ) (Sect. 3.1.1) with a few exceptions (SI Table 7):

- Gypsum: imported from Australia (Winstone Wallboards 2023)
- Urea and single superphosphate: produced in New Zealand (Ledgard and Falconer 2019)
- Lime, dolomite, compost and agricultural salt: modelled to reflect local production and transport

Nitrogen and phosphorous emissions from the use of fertilisers were modelled using the guidelines in EPD International (2019). For CO_2 emissions, following the national guidelines for New Zealand (Ministry for the Environment 2020), the following emission factors were used:

- Limestone and dolomite applications: 0.44 kg CO_2/kg of fertiliser and 0.48 kg CO_2/kg of fertiliser
- Coated and non-coated urea fertilisers: 1.594 kg CO_2/kg of N fertiliser

Compost was used on two orchards. The emission factors for compost production were 0.004 kg CH_4/kg of compost and 0.00024 kg N_2O/kg of compost (Hergoualc'h et al. 2019). Assuming compost producers in New Zealand use best practice methods of windrow composting, only a net 2% of the CH_4 emission factor for composting process was modelled as emitted to air (Jones et al. 2020). In addition, compost also releases nitrous oxide emissions after application; an emission value of 0.047 kg N_2O/kg of compost was used (Mithraratne et al. 2010). With regard to heavy metal emissions from fertiliser application, the commonly used SALCA-HM method (Nemecek et al. 2020) requires detailed site-specific data. Some horticultural LCA studies exclude heavy metal emissions from fertilisers either due to lack of appropriate models for site-specific analysis (Gentil et al. 2020; Martin-Gorriz et al. 2020); others note that heavy metal–related ecotoxicity impacts are usually less significant than other sources in conventional fruit production (Milà I Canals, 2003; Milà I Canals et al. 2006; Meier 2019; Vatsanidou et al. 2020). Moreover, EPD International (2019), which was used as a guideline for this study, did not require heavy metal emissions from fertiliser application to be included. Therefore, these were excluded from the current study.

3.1.3 Fossil fuel and electricity

The main activities carried out on orchards are listed in Table 3. Direct energy use for these activities includes fossil fuels (petrol, diesel and lubricants like grease and oil) and electricity. These fuels are used by both the growers themselves and contractors for specific operations.

All growers provided overall diesel and petrol use on their orchards and also specified the activities undertaken by contractors. The fuel use rates for specific activities were provided by some of the growers and were used to determine average fuel use rates for these activities (Table 3); these values were used as proxy plug-in data for fuel use on orchards for contractor activities. In some cases, the overall fuel use data provided by the growers did not match their disaggregated data by activity; in these cases, the overall fuel use was recalculated based on their activities and the disaggregated fuel use.

Most growers also provided the electricity use for the orchard (i.e. disaggregated from other uses, for example house on the property). In cases where disaggregation of electricity use was not possible, grower estimates were used. Some growers were unable to provide the total electricity use, but instead provided the type of electric motor used (e.g. 1.6 kWh) and the run time of the motor. These data were then used to calculate electricity use per hectare for orchard activities during the study period.

3.1.4 Water

Water used on orchards is sourced either from the public water supply network or from groundwater reservoirs via bores (and in some rare cases, surface water bodies on the property). Activities include irrigation, spraying pesticides and foliar fertilisers, frost protection and fertigation. All growers provided data for total water use on their orchards and the source of water (town supply, groundwater, surface water, etc.). Some growers also provided disaggregated water use data for the different activities. For orchards where water was obtained from the public water supply network, the associated electricity used for treating (purifying) and distributing water was included in the model. For water pumped from underground bores or a surface water body, the electricity or diesel used for pumping water was included in the model.

Table 5 Average agrichemical use on sampled orchards for the study regions

	Total product applied (kg or L/ha)				Total AI applied (kg or L/ha)			
	Minimum	Maximum	Median	IQR	Minimum	Maximum	Median	IQR
Insecticide use								
Far North	2.50E+00	1.43E+02	3.04E+01	2.00E+01	5.00E−01	2.71E+01	5.80E+00	3.80E+00
Mid North	9.00E−01	2.28E+01	5.10E+00	3.60E+00	2.00E−01	4.30E+00	9.00E−01	7.00E−01
Bay of Plenty	3.10E+00	2.93E+02	7.90E+00	1.66E+01	6.00E−01	5.57E+01	1.50E+00	3.10E+00
Herbicide use								
Far North	2.00E−01	3.96E+01	1.24E+01	1.71E+01	1.00E−01	1.35E+01	4.70E+00	6.20E+00
Mid North	4.00E−01	1.25E+01	4.20E+00	4.60E+00	1.00E−01	4.50E+00	1.50E+00	1.70E+00
Bay of Plenty	2.00E−01	6.00E+00	8.00E−01	1.30E+00	1.00E−01	1.80E+00	3.00E−01	2.00E−01
Fungicide (Cu-based) use								
Far North	5.60E+00	1.50E+02	6.11E+01	6.59E+01	3.00E+00	6.58E+01	1.85E+01	2.10E+01
Mid North	7.00E−01	2.56E+01	3.80E+00	4.60E+00	5.00E−01	7.80E+00	3.00E+00	3.50E+00
Bay of Plenty	8.00E−01	1.15E+02	1.20E+01	1.06E+01	3.00E−01	5.49E+01	3.60E+00	4.30E+00
Mineral oil use								
Far North[a]	3.26E+01	8.77E+01	6.01E+01	–	2.68E+01	6.88E+01	4.77E+01	–
Mid North[a]	1.08E+01	1.41E+01	1.24E+01	–	8.90E+00	1.07E+01	9.80E+00	–
Bay of Plenty	2.16E+01	1.04E+02	3.35E+01	3.89E+01	1.78E+01	8.54E+01	2.75E+01	3.20E+01

[a]Not enough data points for IQR calculation

3.2 Orchard lifespan

For the orchard creation stage, data was collected for all the infrastructure materials, and fuel used for the digger, from one of the four supra-massive orchards in the Far North, including typical replacement rates over the projected orchard lifespan of 50 years (Table 4).

Primary input data for the baseline model and the 'supra-massive' orchards are available in the SI Tables 8–11.

4 Results

4.1 Baseline model area–based LCI indicators for the orchard stage

The range and interquartile range (IQR) are often used to demonstrate the variability of a sample, especially when the data is not distributed normally, as often is the case with agricultural data. While the range of values in a dataset (minimum and maximum values) can provide a simple summary of the dispersion of the data, it is still affected by outliers. IQR is a measure of the spread of the middle 50% of the values in a dataset and is therefore unaffected by outliers (Australian Bureau of Statistics 2023) and is considered a robust measure of variability in skewed data distribution. A smaller IQR means the data in the centre of the dataset are more closely clustered together, whereas a larger IQR suggests more dispersed data around the middle and therefore more variability. Tables 5, 6 and 7 present the range, median and IQR values of orchard inputs (per hectare) for the three studied regions. Considerable variability was noted in regional orchard input values. The Far North showed the greatest variability in insecticide, herbicide and fungicide use. The Bay of Plenty and the Mid North had the most

Table 6 Average fertiliser and soil conditioner use on sampled orchards for the study regions

	Minimum	**Maximum**	**Median**	**IQR**
Fertiliser use				
Total product applied (kg or L/ha)				
Far North	7.55E+01	2.57E+03	9.07E+02	9.07E+02
Mid North	6.37E+01	2.47E+03	1.06E+03	5.41E+02
Bay of Plenty	4.72E+02	3.30E+03	1.45E+03	1.15E+03
Total nitrogen applied (kg/ha)				
Far North	9.16E+00	2.10E+02	9.81E+01	5.02E+01
Mid North	6.20E+00	2.48E+02	1.27E+02	8.88E+01
Bay of Plenty	3.17E+01	3.27E+02	1.32E+02	1.13E+02
Total phosphorous applied (kg/ha)				
Far North	3.00E+00	9.23E+01	4.06E+01	2.59E+01
Mid North	2.70E+00	9.60E+01	2.69E+01	2.52E+01
Bay of Plenty	8.50E+00	1.98E+02	4.01E+01	4.69E+01
Soil conditioner (lime/dolomite/gypsum) use				
Total product applied (kg/ha)				
Far North	4.58E+00	4.28E+03	2.66E+01	1.14E+03
Mid North	3.00E+01	3.61E+03	3.63E+02	2.01E+03
Bay of Plenty	2.16E+01	4.62E+03	8.24E+02	1.40E+03

Table 7 Average fuel, water and electricity use on sampled orchards for the study regions

	Minimum	Maximum	Median	IQR
Total diesel use (L/ha)				
Far North	2.07E+02	1.20E+03	5.76E+02	3.39E+02
Mid North	6.25E+01	5.00E+02	2.27E+02	3.55E+02
Bay of Plenty	5.30E+01	4.60E+02	2.37E+02	1.06E+02
Total petrol use (L/ha)				
Far North	3.68E+01	5.05E+02	1.69E+02	2.48E+02
Mid North	2.98E+01	4.22E+02	1.87E+02	9.94E+01
Bay of Plenty	2.63E+01	4.26E+02	1.93E+02	1.54E+02
Total water use (m^3/ha)				
Far North	3.30E+01	6.85E+03	1.58E+03	2.05E+03
Mid North	2.30E+00	6.75E+02	2.55E+02	3.21E+02
Bay of Plenty	1.80E+00	5.69E+02	1.36E+01	2.40E+01
Total electricity use (kWh/ha)				
Far North	1.94E+02	6.01E+03	1.41E+03	1.58E+03
Mid North	2.10E+01	1.88E+02	1.20E+02	9.50E+01
Bay of Plenty	2.60E+00	1.51E+03	1.71E+02	3.27E+02

variable fertiliser and soil conditioner inputs, respectively. Diesel use and petrol use were the most variable in the Mid North and Far North, respectively, whereas water use and electricity inputs were considerably more variable in the Far North than in the other two regions. The low median electricity use in the Mid North may be due to the Maungatapere water scheme, which supplies water to many of the orchards in the region; therefore, only a few orchards require bores and the associated electricity to pump groundwater. The Bay of Plenty orchards used the least water on average because most of their irrigation and spraying water requirements are met with the plentiful rainfall in the region.

4.2 Baseline model LCIA

The regional and national impact scores[4] are presented in Table 8.

4.2.1 Climate change

The main contributing sub-stages/inputs to the climate change impact category in all three regions are fuel and fertilisers (Fig. 1). The fuel use impacts are primarily due to CO_2 emissions from fuel combustion (mainly diesel) in agricultural machinery used on orchards.

All fertiliser-related impacts are due to emissions of CO_2 and N_2O to air. These impacts are related to both 'non-application' activities (production/formulation, and transport) and application on the orchard. Of these, the non-application activities account for > 61% of the total fertiliser-related impacts (Fig. 2). Figure 3 shows the variability between relative contributions (%) of production and transport of individual fertilisers and soil conditioners to overall non-application climate change impacts.

McNally and Gentile (2021) report that avocado trees and associated shelterbelt vegetation can act as a carbon sink for the first 28 years of the orchard's life. Using their data on carbon storage in avocado trees and shelterbelts, an avocado orchard could store between 0.051 and 0.077 kg CO_2 eq./kg avocados produced in an orchard with topped and untopped shelterbelts, respectively. Although this carbon storage was not included in the baseline modelling for this study, the values are equivalent to a carbon offset of 12% or 18% for an orchard with topped or untopped shelterbelts, respectively, when using the national climate change score for NZ avocados developed in this study (0.43 kg CO_2 eq./kg avocados). Any such calculation would also need to account for potential soil carbon changes associated with establishment of avocado orchards, hence accounting for impacts related to land use change, which was outside the scope of this study (Sect. 2.1).

4.2.2 Eutrophication

Fertiliser use and soil conditioner use contribute the most to the eutrophication impact category in all three regions (Fig. 4), followed by fuel use. The majority of the impacts

Table 8 National impact scores for New Zealand–produced avocados

	Climate change (kg CO_2 eq./kg avocados)	Eutrophication (kg phosphate eq./kg avocados)	Water use (m^3 world equivalent/kg avocados)	Freshwater ecotoxicity (CTU_e/kg avocados)	Terrestrial ecotoxicity (kg 1,4-DB eq./kg avocados)
Far North	4.60E−01	2.90E−03	7.50E−01	1.08E+04	6.10E+00
Mid-North	4.60E−01	3.40E−03	2.00E−01	3.75E+03	4.30E+00
Bay of Plenty	4.00E−01	3.30E−03	1.40E−01	6.40E+03	3.80E+00
National	4.30E−01	3.30E−03	3.10E−01	6.93E+03	4.50E+00

[4] The water use results use sub-national factors and are therefore updated from Majumdar et al. (2022).

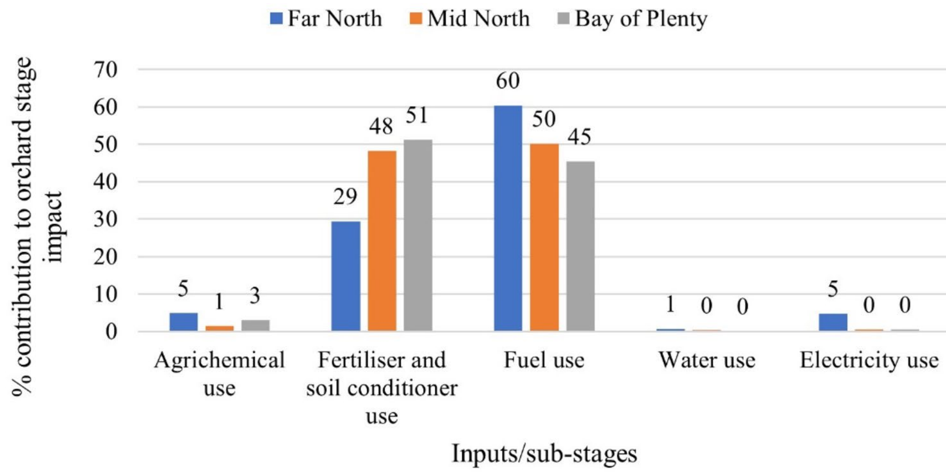


Fig. 1 Contribution (%) of inputs/sub-stages to overall climate change impact of the orchard stage

are from fertiliser application (Fig. 5) and are due to emission of nitrates, phosphates and phosphorous to freshwater. The remaining impacts are from emissions of ammonia, nitrous oxide, nitrogen oxides and other nitrogen compounds to air.

4.2.3 Water use

The water use impact scores for the orchard stage are highest in the Far North followed by the Mid North and Bay of Plenty (0.75 m^3 world equivalent/kg avocados, 0.2 m^3 world equivalent/kg avocados and 0.14 m^3 world equivalent/kg avocados, respectively). Figure 6 shows the contribution (%) of direct and indirect water uses to the total water use impact score in the three regions. Indirect water use contributes the most to this impact category in all three regions.

4.2.4 Freshwater ecotoxicity

While agrichemical use is the largest contributor to freshwater ecotoxicity in the Far North and Bay of Plenty, fertiliser and soil conditioner inputs contribute slightly more to the impact score in the Mid North (Fig. 7). The difference in relative contributions of these two types of input largely reflects the varying quantities of copper-based fungicides used on orchards in the different regions.

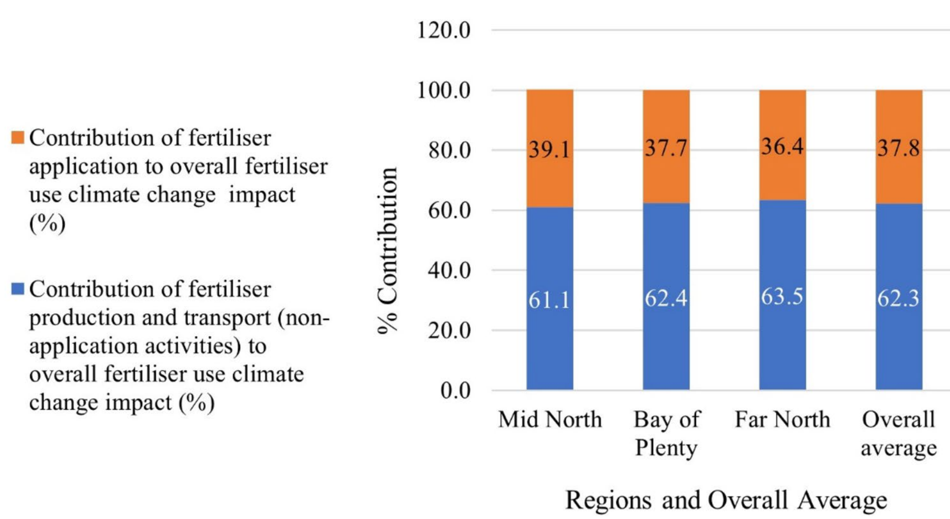


Fig. 2 Contribution of fertiliser production, transport and use (application) to overall fertiliser use impacts on orchards

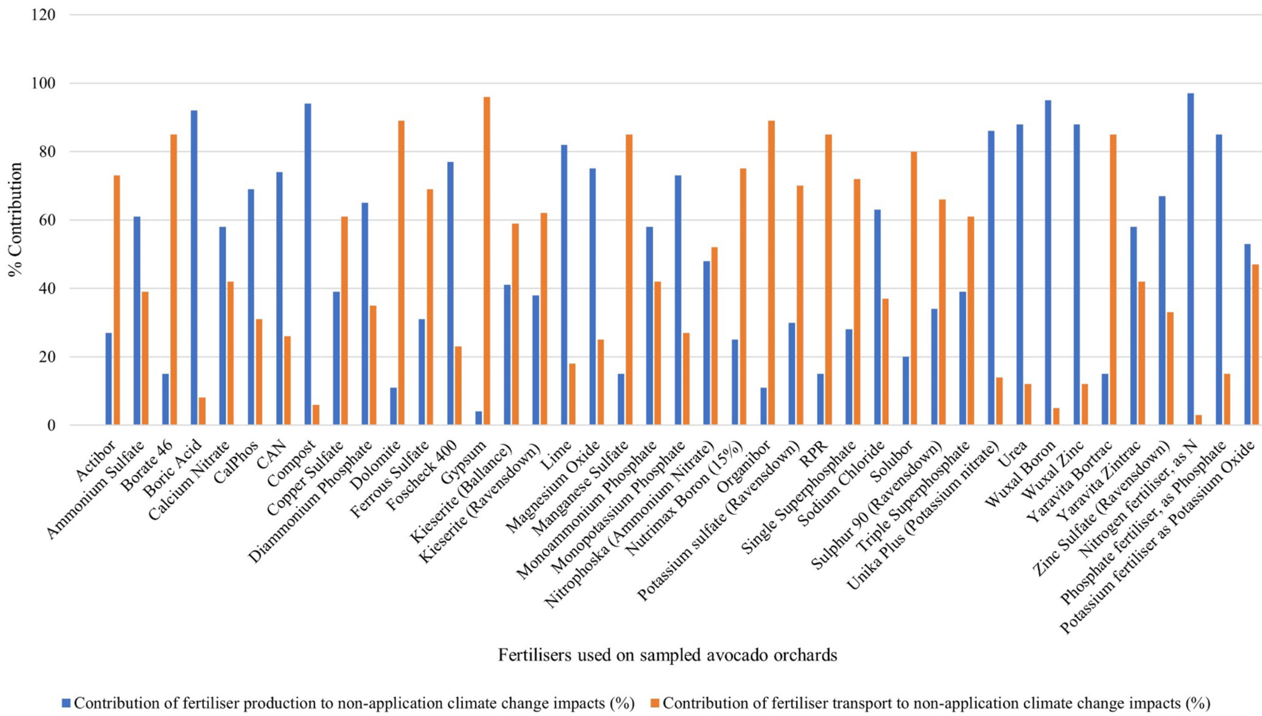


Fig. 3 Relative contributions (%) of production and transport of individual fertilisers and soil conditioners to overall non-application climate change impacts

4.2.5 Terrestrial ecotoxicity

Terrestrial ecotoxicity impacts are mainly due to emissions of heavy metals (particularly copper) to air during the manufacture of agrichemicals and fertilisers (Fig. 8). Fuel use is also a contributor to these impact category results.

4.3 Variability in impact scores between orchards in the three studied regions

The impact scores varied between orchards in each of the three studied regions (Table 9). The Mid North showed the highest variability amongst orchards in the climate

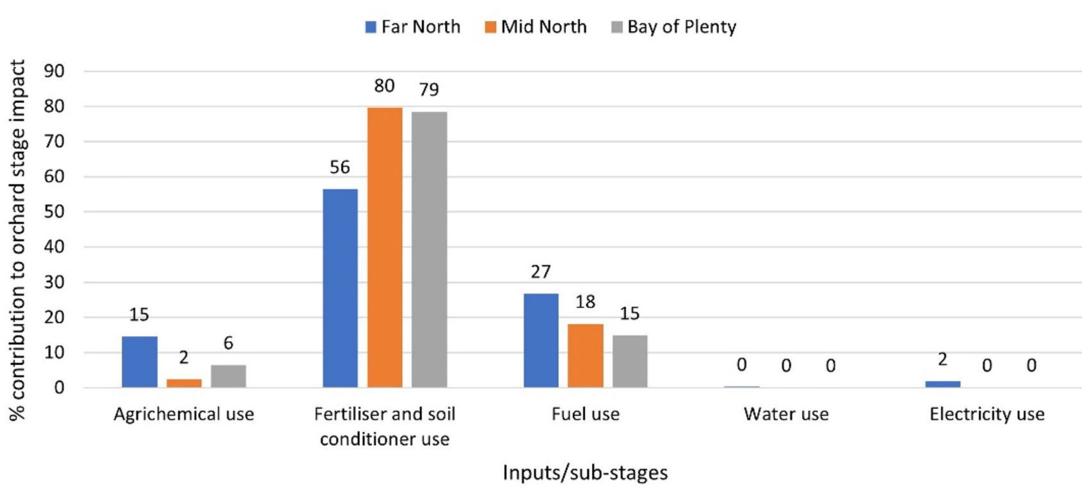


Fig. 4 Contribution (%) of inputs/sub-stages to overall eutrophication impact of the orchard stage

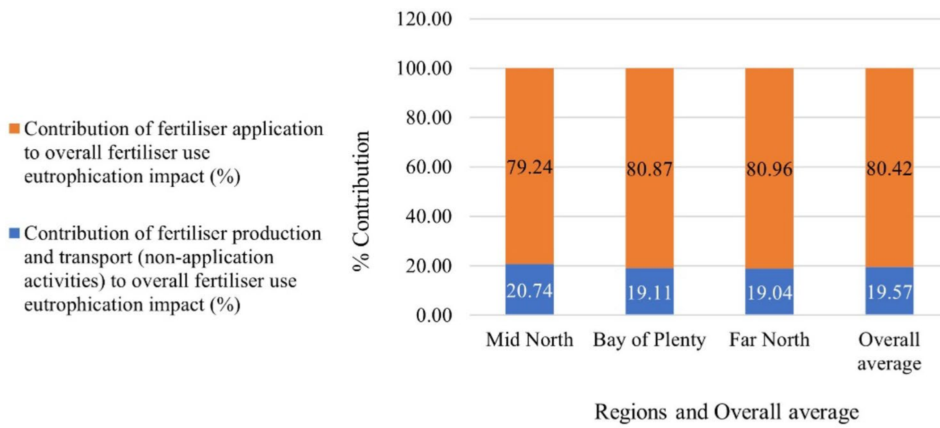


Fig. 5 Contribution of fertiliser application and non-application activities (production and transport) to overall fertiliser use eutrophication impact on orchards

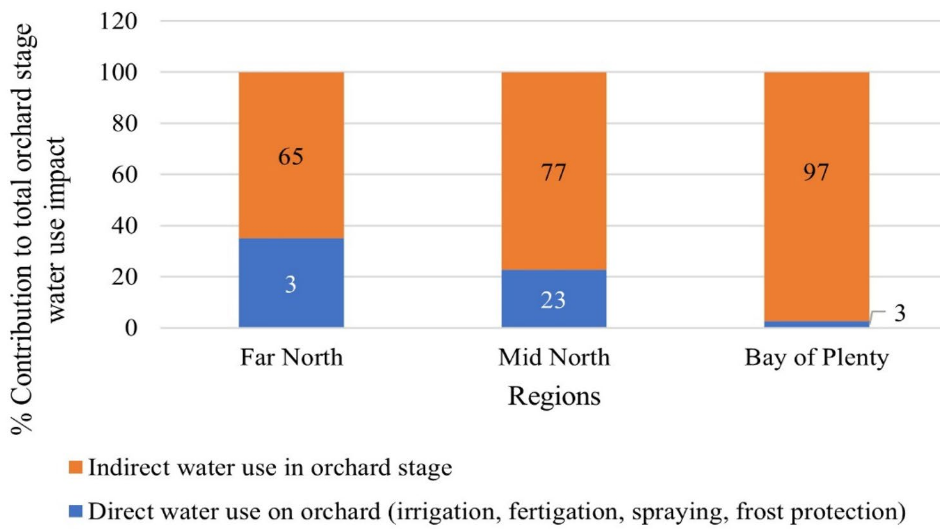


Fig. 6 Relative contributions of direct and indirect water uses to the total impact score for the orchard stage for the three regions

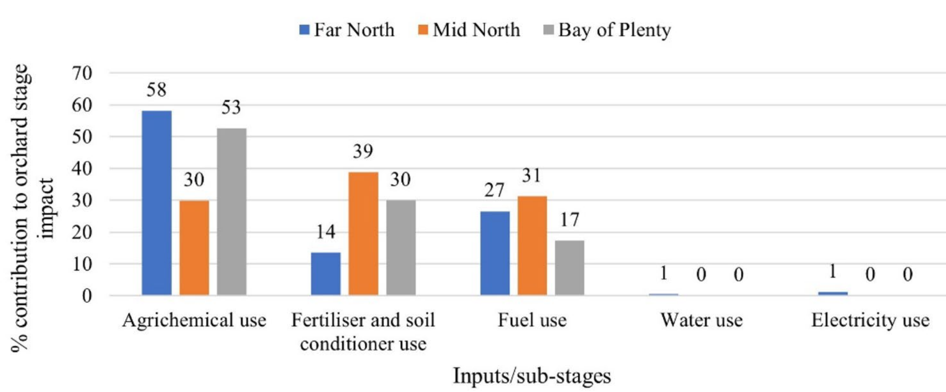


Fig. 7 Contribution (%) of inputs/sub-stages to overall freshwater ecotoxicity impact of the orchard stage

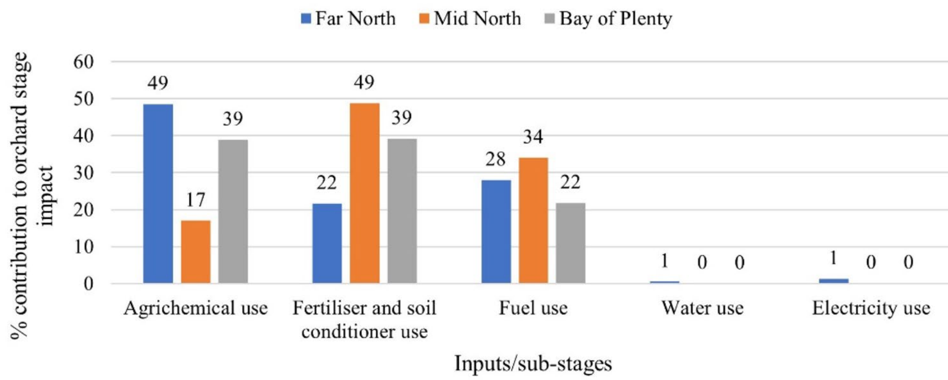


Fig. 8 Contribution (%) of inputs/sub-stages to overall terrestrial ecotoxicity impact of the orchard stage

change impact category, while the eutrophication impacts were most variable in the Bay of Plenty. The impact scores in the other three categories were most variable in the Far North.

4.4 Baseline model co-relation between orchard productivity and environmental impacts

The environmental impact scores were plotted against the orchard yields for each of the 49 orchards (Fig. 9). The climate change and eutrophication scores decrease as orchard yields increase (Fig. 9a, b). The water use, freshwater and terrestrial ecotoxicity impact scores increase with yields, and then decline when yields exceed 13,000–15,000 kg/ha (Fig. 9c–e).

4.5 Impacts across orchard lifespan

The contribution of each orchard stage to the total impact scores for the 50-year orchard lifespan is shown in Fig. 10, modelled for the Far North orchards. As expected, the commercial stage is the largest contributor for all impact categories, followed by the orchard establishment stage.

The impact scores per kg of avocados for an averaged year of the orchard life were derived by calculating the total impacts across the 50-year orchard life for 1 ha of orchard area, divided by the total avocado production over the same time period (Table 10). The average impact per kg avocados is 13–26% higher than the baseline results for the five impact categories.

Table 9 Ranges of—and variability in—impact scores between orchards in the three studied regions

Impact categories	Regions	Minimum	Maximum	Median	IQR
Climate change (kg CO_2 eq./kg avocados)	Far North	2.10E−01	7.40E−01	4.70E−01	2.20E−01
	Mid North	2.20E−01	7.10E−01	4.70E−01	3.60E−01
	Bay of Plenty	1.60E−01	7.80E−01	4.00E−01	2.50E−01
Eutrophication (kg phosphate eq./kg avocados)	Far North	1.10E−03	5.40E−03	2.60E−03	1.20E−03
	Mid North	9.00E−04	6.60E−03	3.40E−03	1.00E−03
	Bay of Plenty	8.00E−04	1.09E−02	3.50E−03	2.20E−03
Water use (m^3 world equivalent/kg avocados)	Far North	9.00E−02	2.06E+00	7.80E−01	7.40E−01
	Mid North	5.00E−02	5.00E−01	2.00E−01	2.00E−01
	Bay of Plenty	3.00E−02	5.00E−01	1.10E−01	1.30E−01
Freshwater ecotoxicity (CTU_e/kg avocados)	Far North	2.20E+03	3.38E+04	6.09E+03	7.98E+03
	Mid North	8.22E+02	6.48E+03	3.86E+03	3.09E+03
	Bay of Plenty	9.82E+02	2.48E+04	5.13E+03	4.17E+03
Terrestrial ecotoxicity (kg 1,4-DB eq./kg avocados)	Far North	1.70E+00	1.66E+01	3.90E+00	3.30E+00
	Mid North	7.00E−01	1.26E+01	2.70E+00	1.70E+00
	Bay of Plenty	9.00E−01	1.27E+01	3.10E+00	2.60E+00

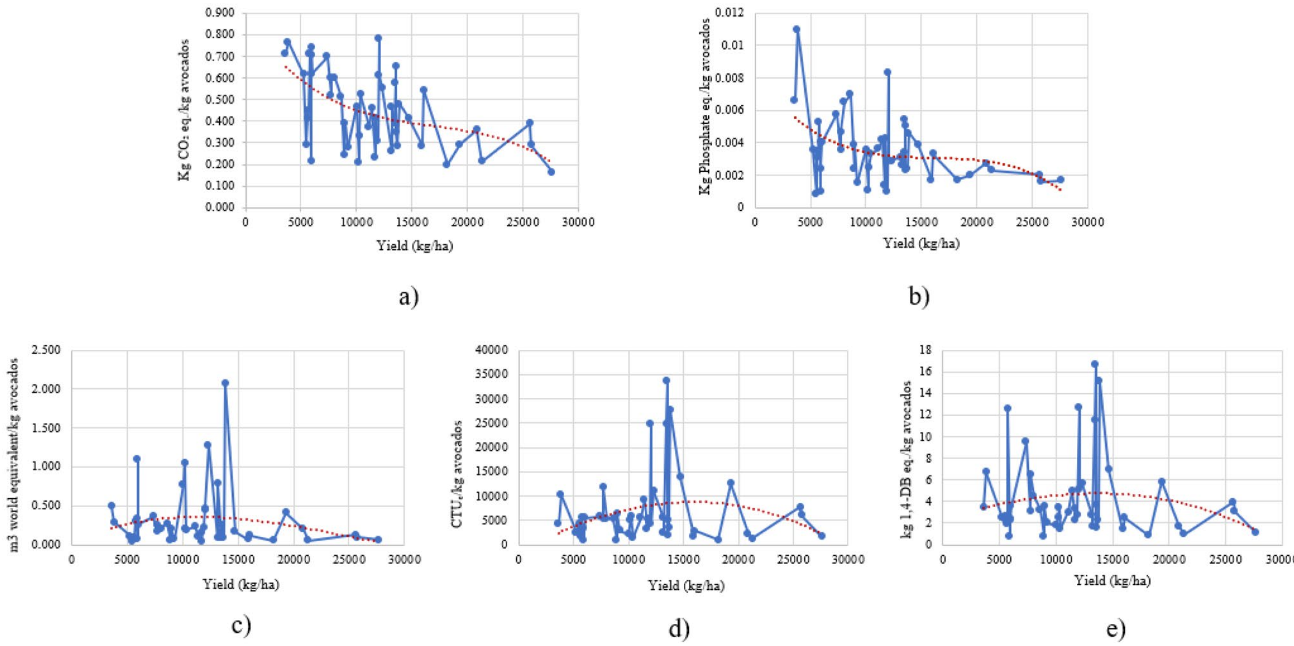


Fig. 9 Co-relation between impact category scores and yields (kg/hectare) of individual orchards in the baseline model (**a** climate change, **b** eutrophication, **c** water use, **d** freshwater ecotoxicity and **e** terrestrial ecotoxicity)

It is important to note that the climate change impacts were modelled excluding biogenic carbon. Alternatively, the biogenic carbon in the wooden posts (used for fencing the orchard) could be modelled as going to a managed sanitary landfill at end of life. With a best-case scenario of no decay for at least 100 years, the climate change score for the orchard creation stage reduces by 42%, and the orchard creation stage contribution to total impacts across the orchard lifespan reduces to 3.4% (assuming 50% carbon content (dry matter basis) of the wood). In reality, nearly half of the waste generated on New Zealand farms (including orchards) is sent to unmanaged landfills known as farmfills, with most of the rest disposed by 'open burning' on farms (Ministry for the Environment 2021). In the former case, it is likely that some carbon would be released as methane and carbon dioxide from

Fig. 10 Contribution of each orchard stage to total impacts across orchard lifespan (calculated for 1 ha over 50 years), modelled for Far North orchards

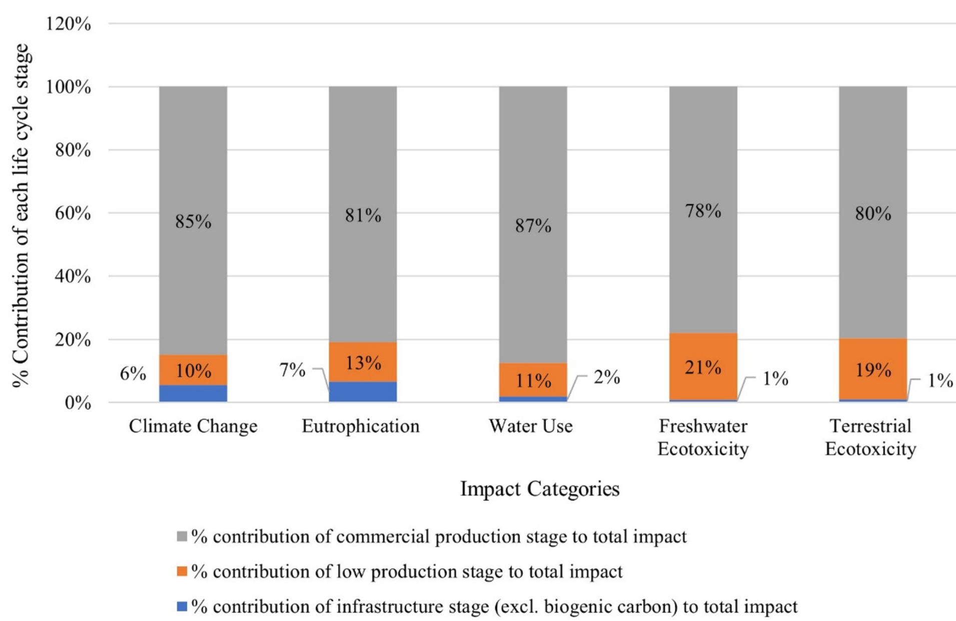


Table 10 Impact assessment scores per kg avocados, averaged across the orchard lifespan, for orchards in the Far North

	Infrastructure impact (excl. biogenic carbon) (per ha)	Total impact over 6 low production years	Total impact over 44 commercial production years	Total impact over orchard lifespan	Impact per kg avocados for any productive year (weighted average)	Baseline average impacts of the Far North (per kg avocados/year)[a]	% increase of weighted average from baseline
GWP (kg CO_2 eq.)	1.98E+04	3.30E+04	2.98E+05	3.51E+05	5.30E−01	4.60E−01	16
Eutrophication (kg phosphate eq.)	1.60E+02	3.03E+02	1.95E+03	2.41E+03	4.00E−03	3.00E−03	26
Water use (m^3 world equivalent)	1.05E+04	5.97E+04	4.86E+05	5.56E+05	8.40E−01	7.50E−01	13
Freshwater ecotoxicity (CTU_e)	8.28E+07	1.90E+09	7.00E+09	8.98E+09	1.36E+04	1.08E+04	26
Terrestrial ecotoxicity (kg 1,4-DB eq.)	4.96E+04	9.68E+05	3.98E+06	5.00E+06	8.00E+00	6.14E+00	23

[a]Values for a commercially productive year

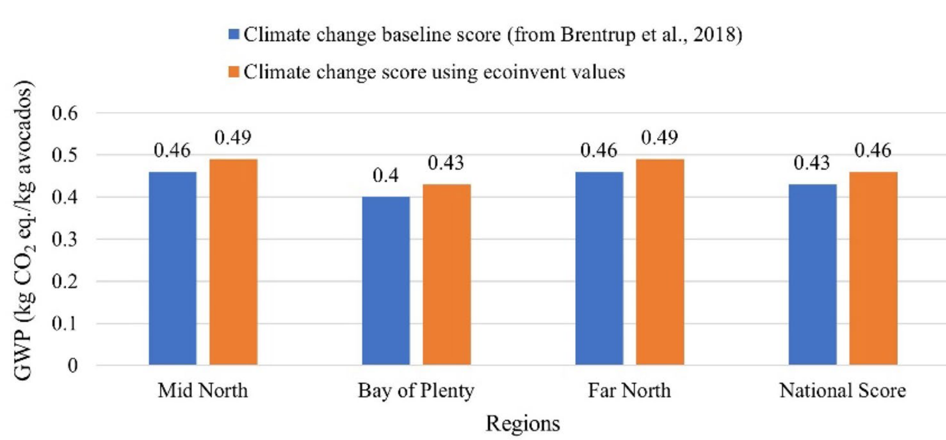
the decomposing wood; however, most of the carbon would remain sequestered (O'Dwyer et al. 2018).

4.6 Sensitivity analyses for the baseline

As mentioned earlier, for the production of fertilisers in the baseline study, the climate change emission factors provided by Brentrup et al. (2018) were used in the analysis. The climate change scores of the original ecoinvent datasets were compared with the respective datasets used in the baseline (i.e. the ecoinvent datasets which had been amended to represent the climate change values in Brentrup et al. 2018). Apart from lime and ammonium sulfate (where the ecoinvent datasets had lower values than the baseline datasets), all other fertiliser product climate change values were higher (by up to 362%) when using the original ecoinvent datasets.

Given the significant differences in the ecoinvent and Brentrup et al. (2018) values, a sensitivity analysis was conducted using the original ecoinvent values to understand the potential difference in results when using these different datasets. Figure 11 shows that the climate change impact scores increased by 7% for the national and regional results when using the original ecoinvent datasets compared with the baseline values.

Fig. 11 Change in climate change impact scores from baseline, when using the original ecoinvent datasets for fertilisers, instead of the Brentrup et al. (2018) values used in the baseline



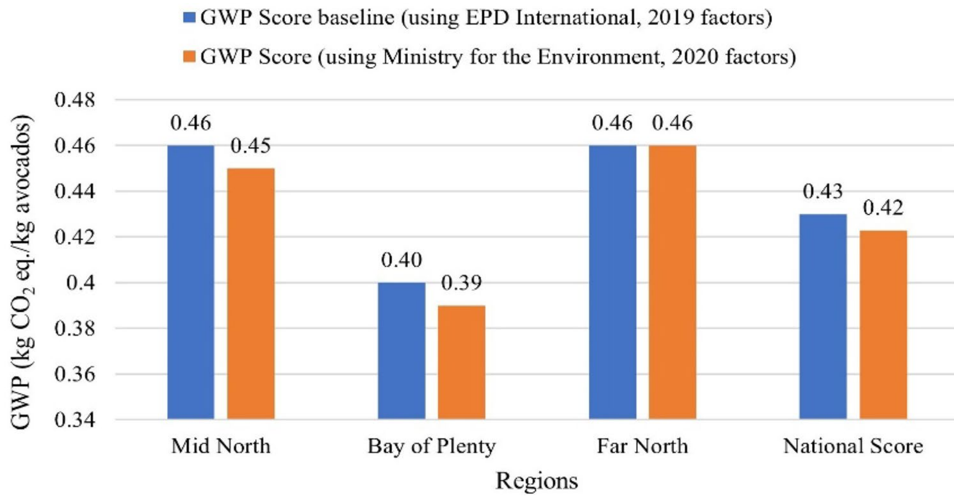


Fig. 12 Climate change impact scores for baseline, and when using the Ministry for the Environment (2020) emission factors for nitrogen fertiliser use

SI Table 13 lists the emission factors for the use of nitrogen fertilisers provided in EPD International (2019) and Ministry for the Environment (2020). The table shows that the values of climate change emission factors for all fertilisers listed in the EPD International (2019) guidelines are higher than the corresponding values of the Ministry for the Environment (2020) (which are provided just for urea (no UI), urea (UI) and non-urea fertilisers (generic)) except for that of ammonium sulfate which is slightly lower. A sensitivity analysis was therefore conducted to determine the change in regional and national impacts from baseline levels, when using the Ministry for the Environment (2020) instead of the EPD International (2019) factors for the nitrogen fertilisers.

Figure 12 shows that, when using the Ministry for the Environment (2020) emission factors, the regional GWP scores decreased by 2% and 3% in the Mid North and Bay of Plenty, respectively, and remained unchanged for the Far North. When scaled up to obtain a weighted average national score, there was a small (2%) decline in the baseline national score for the orchard stage when using the alternative Ministry for the Environment (2020) emission factors.

5 Discussion

The baseline results show that the fertiliser and fuel inputs are hotspots for all impact categories except water use, and agrichemical use is an additional hotspot for the ecotoxicity impacts. The water use impact is dominated by indirect water use, irrespective of whether the orchards are irrigated or not.

5.1 Comparison with other studies

Of the five impacts assessed in this study, climate change was the only category reported in all other avocado-related LCA literatures. The climate change impact scores calculated in this study are at the lower end of the range of results reported by similar studies conducted internationally (0.2–2.4 kg CO_2 eq./kg avocados) (Table 11). Although all the studies used the same unit of measurement (kg CO_2 eq./unit of fruit), these results should be compared with caution due to differences in the scope of different studies and, particularly, in system boundaries.

Frankowska et al. (2019) found that irrigation-related emissions accounted for most of the on-farm climate change impact. This is not surprising since they studied avocados imported from water-scarce countries that need to use widespread irrigation to grow avocados. Irrigation was the main contributor to climate change impacts in one of the Australian studies as well, followed by fertiliser use (D'Abbadie and Akbari 2023). In contrast to these two papers, in this study, fertiliser/soil conditioner use and fuel use were hotspots for the climate change impact while irrigation-related emissions were negligible. This is because most of the water used on orchards was for spraying agrichemicals and foliar fertilisers—relatively less water was pumped for irrigation. In the Bay of Plenty particularly (where most of NZ's current avocado production occurs), most orchards primarily use rainwater for growing the avocados and therefore have smaller direct water use values. Other studies also identified fertiliser production and use and fuel use as the main sources of impacts associated with growing avocados (Astier et al. 2014; Esteve-Llorens et al. 2022; Graefe et al. 2013; Solarte-Toro et al. 2022). Specifically, mineral fertiliser non-application activities (mainly production) usually contribute the most to the climate change impact, and a similar trend has been noted in LCAs of other horticultural products like peaches, apples, sweet cherries, plums, pears, oranges and bananas (Vinyes et al. 2015, 2017; Alaphilippe et al. 2016; Yan et al. 2016; Goossens et al. 2017; Svanes and Johnsen 2019; Vatsanidou et al. 2020). Horticultural LCA studies in NZ for kiwifruit and

Table 11 Climate change impact scores from different avocado-related LCA studies identified in the literature review

Citation	Climate change impact (kg CO^2 eq./kg avocados)
D'Abbadie and Akbari (2023)	0.32 (15-year average); 0.29 (peak production year)
Esteve-Llorens et al. (2022)	1.09
Solarte-Toro et al. (2022)	0.6
Bendotti Avocado (2021)	0.62
Carbon Neutral Avocados (2021)	1.23
Frankowska et al. (2019)	2.4
Hadijan et al. (2019)	1.38
Bell et al. (2018)	0.45
Astier et al. (2014)	0.41 (organic); 0.54 (conventional)
Graefe et al. (2013)	0.2
Bartl et al. (2012)	0.5
Stoessel et al. (2012)	1.3
Audsley et al. (2009)	0.43 (Europe); 0.88 (global)

apples have also found fertiliser and soil conditioner production and use (and in the case of apples, pesticide production as well) to be the main contributor to climate change for the orchard stage (Milà I Canals et al. 2006; Mithraratne et al. 2010; Müller et al. 2015).

The eutrophication results in the current study are in line with the results found in literature. In an LCA study conducted on the fertiliser life cycle, Hasler et al. (2015) noted that on-field fertiliser application had a distinctly higher contribution to eutrophication impacts compared to other life cycle stages. Studies assessing eutrophication impacts of avocado production in particular, as well as other perennial crops, also reflected the same results (Vinyes et al. 2015; Alaphilippe et al. 2016; Goossens et al. 2017; Esteve-Llorens et al. 2022). With regard to ecotoxicity impacts, Esteve-Llorens et al. (2022) found that emissions from fertiliser and agrichemical uses (to a lesser extent) were the main contributors to aquatic ecotoxicity. In the current study, however, agrichemical production was generally the major contributor to freshwater ecotoxicity in two regions, followed by fertiliser production and fuel use. This is potentially related to the different methodological choices adopted in the two studies to assess pesticide and fertiliser emissions to different environmental compartments.

Studies that assess the environmental impacts of multiple products usually report avocados with very high (if not the highest) water use impacts (Stoessel et al. 2012; Bell et al. 2018; Frankowska et al. 2019; Hadijan et al. 2019). As Frankowska et al. (2019) noted, the high avocado water footprint for avocados could be reduced by sourcing them from countries that are less water stressed. In water-scarce regions, with low rainfall or sparse rainfall harvesting practices, more water must be pumped from aquifers. The current study showed that NZ growers use relatively lesser water per kg of avocados than other countries. For example, the average (volumetric) water use in the Far North (which has the highest water use values in the three studied regions) is 2039 m^3/ha compared with the lowest value of 8285 m^3/ha reported by Esteve-Llorens et al. (2022) for avocado cultivation in Peru. It is also worth noting that, at impact assessment, the use of New Zealand sub-national versus national characterisation factors for the water use assessment makes a significant difference to the results: the water use impact score was 135% higher (0.73 m^3 world equivalent/kg avocados) when using the national (unspecified) rather than sub-national AWARE characterisation factors. This sensitivity of water use impact scores to localised AWARE characterisation factors was also noted by Esteve-Llorens et al. (2022).

5.2 Towards the use of continuous improvement indicators for NZ avocado orchards

This LCA study resulted in the development of regional- and national-level impact scores for NZ avocado production, assessed for the five studied impact categories. These impact categories could be used as indicators (and their scores as benchmarks) for a future programme aimed at monitoring and facilitating improvement in the environmental performance of NZ avocado production. Other works have indicated that benchmarking can be an effective tool in encouraging private actors (such as farmers) to improve their practices (Wu et al. 2015; World Benchmarking Alliance 2022). The following sections discuss additional considerations when using the study results to support the development of such indicators and benchmarks.

5.2.1 Variability between orchards

There was considerable variability between orchards in terms of inputs (Sect. 4.1 and Tables 5, 6 and 7) and impacts

(Sect. 4.3 and Table 9). To further illustrate this point, Fig. 13 shows the fuel use across the 49 orchards assessed in the study. It can be seen that there is high variability between individual orchards as well as between regions. Orchards in the Far North, for example, use more fuel than the other two regions. This is because the management practices are different in the Far North: the orchards in this region are larger, more intensive and commercially oriented than the traditionally family-owned and hobby-farmed smaller orchards in the Bay of Plenty.

This variability can be attributed to land, soil and climatic conditions and may also be related to economies of scale on larger orchards, as well as different management practices. For example, the largest input-related variability was noted in soil conditioners—this is potentially because unlike other inputs, soil conditioners are typically used only once every 2 years or 3 years on any orchard block. Thus, within the data collection period for this study, some growers had used them in varying quantities, while others had not. Variability in both inputs and impacts was more pronounced in the Bay of Plenty, where most of the growers are smallholders and orchard management practices can be very different between growers. This contrasts with the Far North and Mid North, where avocado orchards are generally larger, have more commercial operations and therefore may have more homogenous practices.

Such variability in agricultural systems has been noted elsewhere in the literature (Astier et al. 2014; Bojacá et al. 2014; Yan et al. 2016; Notarnicola et al. 2017; Poore and Nemecek 2018; Cucurachi et al. 2019; Green et al. 2021). Therefore, careful consideration should be given to the variability amongst NZ avocado orchards when choosing indicators to drive continuous improvement at individual orchard or regional level. The most feasible improvement options may vary between regions and management regimes (e.g. the large commercial operations in Northland and the smaller family run businesses in the Bay of Plenty).

5.2.2 Productivity and eco-efficiency as indicators

The co-relation analysis between orchard productivity and environmental impact scores (Sect. 4.3) showed that climate change and eutrophication scores (per kg avocados) decreased with increasing yields. However, the other three impact category scores increased with increasing productivity up to 13,000–15,000 kg/ha, after which they declined. This suggests that increased orchard productivity may be associated with improved environmental performance, particularly at yields higher than 13,000–15,000 kg/ha. Further research is required to better understand the relationship between these variables. However, one inference is that the environmental performance of NZ avocado orchards can be improved by increasing productivity sustainably. This concept of 'sustainable intensification' has been discussed in horticultural and agricultural literature (Dicks et al. 2019; Hasler et al. 2015; Iglesias & Echeverria 2022; Li et al. 2022) and has even been adopted as a targeted policy goal (Garnett et al. 2013). Sustainable intensification can be achieved by improving orchard management practices (Yan et al. 2016), possibly with little to no increase in inputs (Svanes & Johnsen 2019). Therefore, orchard productivity is a possible indicator for supporting continuous improvement, alongside environmental impact scores. Extending this idea, eco-efficiency is an approach which considers the economic value of a product in relation to its environmental impacts, most commonly by dividing the economic value of the

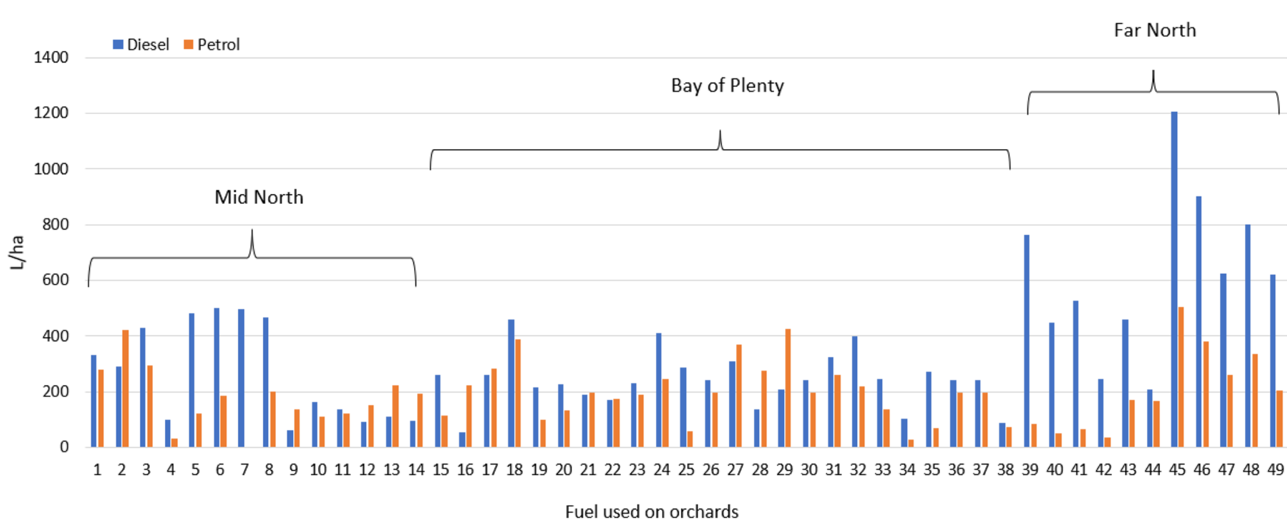


Fig. 13 Fuel use (petrol and diesel) on each of the 49 orchards in this study

product by its environmental ‘score’. For example, Müller et al. (2015) divided the net profit of kiwifruit (in NZD per hectare) by the GWP value (per hectare) to investigate the eco-efficiency of NZ-produced kiwifruit. This indicator could provide combined environmental and economic information to growers.

It is important to note that alternate bearing is a challenge to using either of these indicators on an annual basis in the NZ avocado sector. However, when calculating the sector's IBI (see Sect. 2.3.1), if the orchard yield increases 3 years in a row, then it is considered to have an IBI of 0 as the increasing yield is seen as an improvement in production rather than irregular bearing (Pers. Comm., NZ Avocado, September 2021). Thus, tracking the results through both ‘on’ and ‘off’ years and benchmarking against the sector's rolling average score over (at least), a 2-year period can help the growers understand their eco-efficiency through the irregular bearing cycle. This will also ensure appropriate representation in the indicator results of infrequent activities such as application of soil conditioners.

5.2.3 Lifespan of orchard

The results of the impact assessment across the whole orchard life (Sect. 4.4) demonstrated that it is worthwhile to consider the entire lifespan of the orchard when considering improvement options. But, orchard establishment and the early low production stage are ‘in the past’ for most growers and its assessment is irrelevant in terms of improvement options. Also, as mentioned in Sect. 1.2, young orchards (in the orchard creation and establishment stage) have very low yields, so measuring their environmental impacts using a mass-based FU and then benchmarking these scores against the sector average would be an unfair comparison. Therefore, a solution could be to assess the young orchards (3 years old or less) separately using an area-based FU (1 ha of worked avocado orchard); this could be benchmarked against the industry average of the other young orchards in the region using the same area-based FU. Figures 14, 15, 16, 17 and 18 demonstrate this approach for the four supra-massive orchards in the Far North and also show how they compare with the other orchards (in commercial production) in the Far North on an average per hectare basis for climate change. It can be seen that the average climate change score of the four supra-massive orchards is lower than that of the orchards in commercial production when calculated on an area basis. In contrast, the average eutrophication, water use and ecotoxicity impact scores of the four orchards are higher than the corresponding average impact scores of the orchards in commercial production. At an individual orchard level, the high impact scores (except for water use) of orchard ‘a’ relative to orchards ‘b’, ‘c’ and ‘d’ are particularly noteworthy; orchards b, c and d are owned and managed by the same company, and orchard a is under a different management.

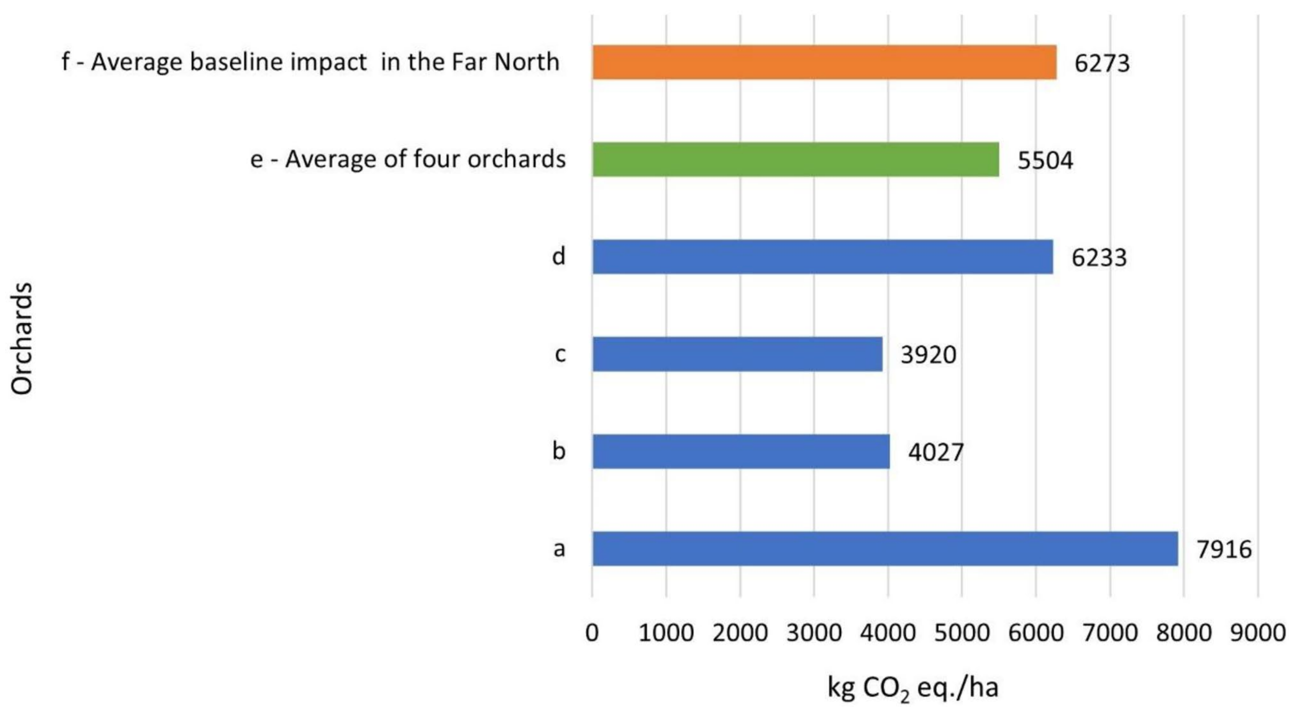


Fig. 14 Climate change impacts per hectare of the four ‘supra-massive’ orchards (**a–d**), average of the four orchards (**e**), compared to the average environmental impact per hectare of baseline orchards in the Far North (**f**)

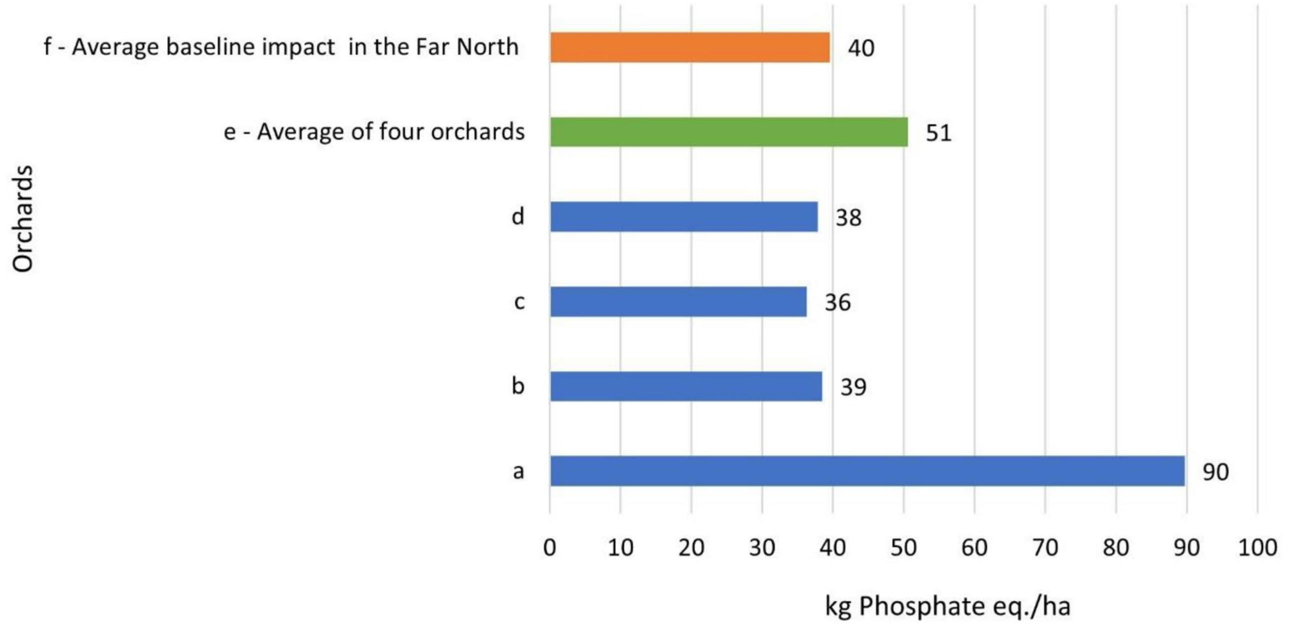


Fig. 15 Eutrophication impacts per hectare of the four 'supra-massive' orchards (**a**–**d**), average of the four orchards (**e**), compared to the average environmental impact per hectare of baseline orchards in the Far North (**f**)

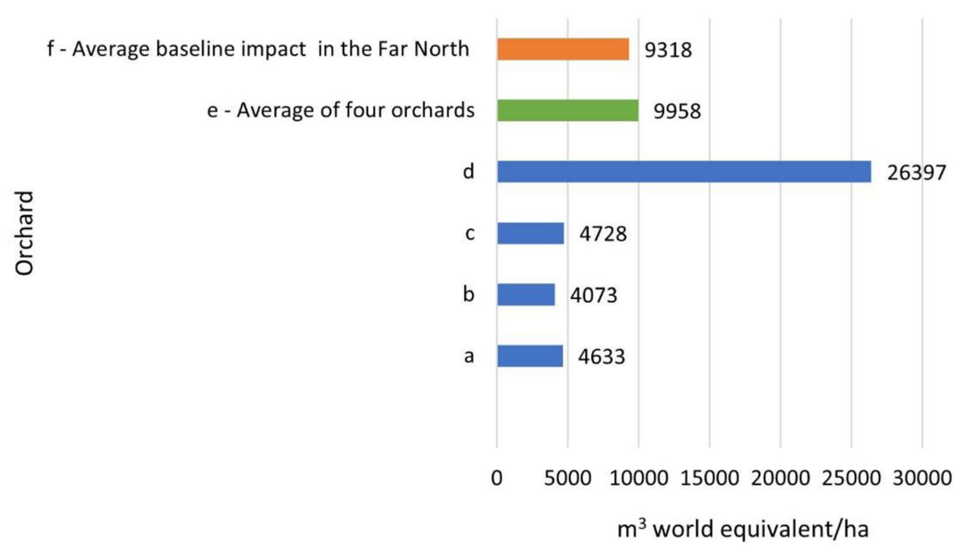
5.2.4 Improvements to the indicators and other recommendations

The environmental impact category indicators used in this study can be refined by addressing certain methodological limitations.

For the climate change indicator, carbon sequestration in avocado orchards could be included by calculating the carbon stored in the avocado trees, in the topped and untopped shelterbelt vegetation on the orchard, and any changes in soil carbon levels. Biogenic carbon stored in wooden posts should also be considered for carbon sequestration potential.

With respect to eutrophication impacts, current methods are not particularly relevant for New Zealand (Sect. 2.2). However, in the absence of a suitable site-specific method, the CML 2001 method is recommended as a precautionary approach (Payen and Ledgard 2017).

Fig. 16 Water use impacts per hectare of the four 'supra-massive' orchards (**a**–**d**), average of the four orchards (**e**), compared to the average environmental impact per hectare of baseline orchards in the Far North (**f**)



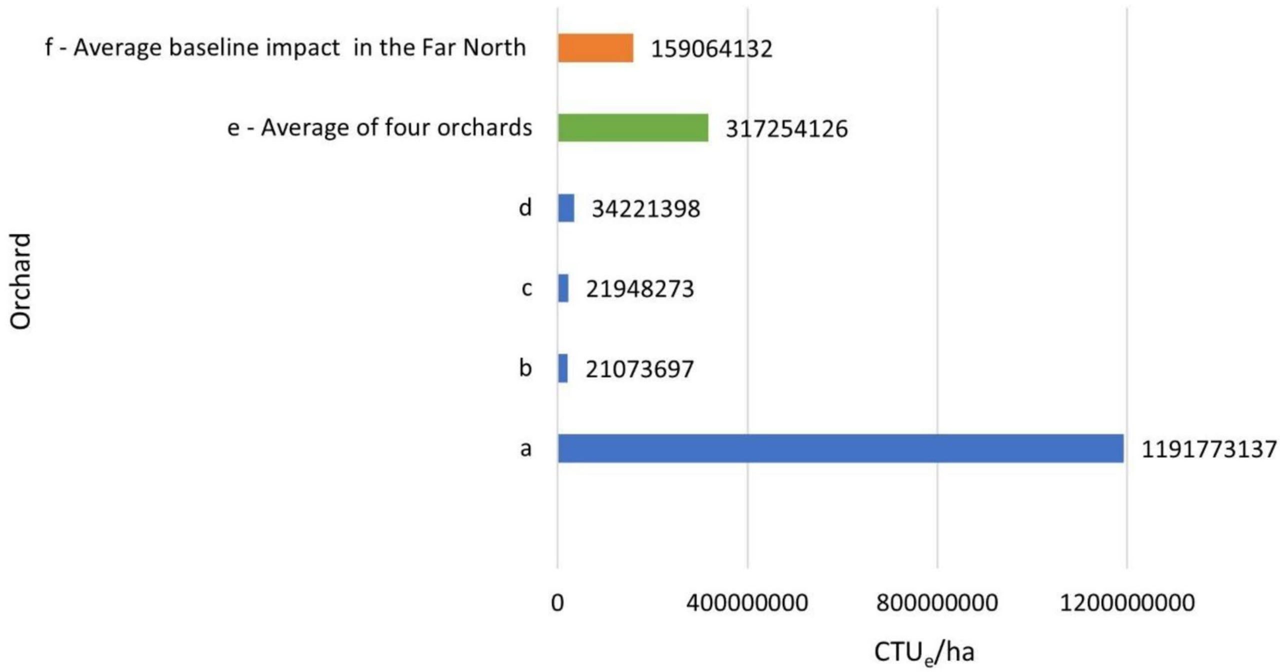


Fig. 17 Freshwater ecotoxicity impacts per hectare of the four 'supra-massive' orchards (**a**–**d**), average of the four orchards (**e**), compared to the average environmental impact per hectare of baseline orchards in the Far North (**f**)

For water use, watershed-level characterisation factors are most appropriate when conducting water footprints because national-level characterisation factors can result in large uncertainty in the results, particularly for countries where watersheds have quite different water scarcity values (Boulay and Lenoir 2020). Moreover, an annual water use

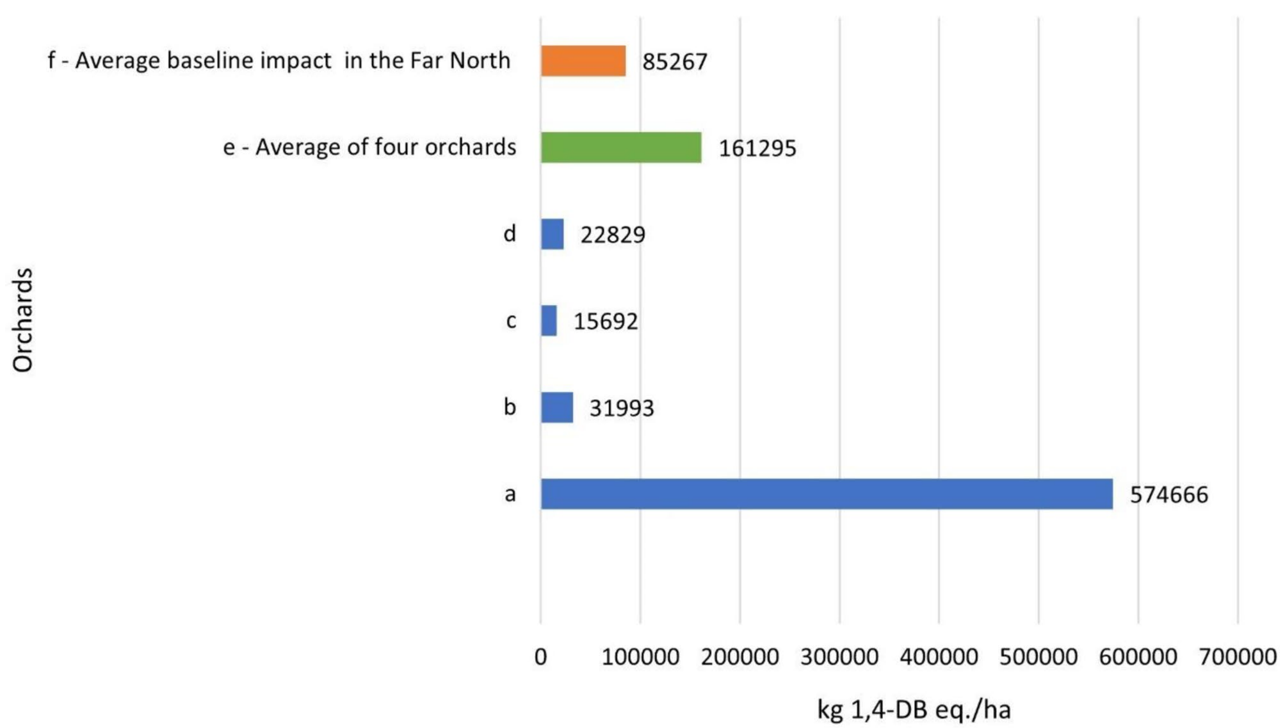


Fig. 18 Terrestrial ecotoxicity impacts per hectare of the four 'supra-massive' orchards (**a**–**d**), average of the four orchards (**e**), compared to the average environmental impact per hectare of baseline orchards in the Far North (**f**)

value was collected for this study period of 2018–2019, as monthly and seasonal values were unavailable. However, water availability changes with seasons through the year and therefore incorporating the temporal aspect in water footprints would contribute to a more accurate impact assessment of water use. Therefore, while the water use results of the current study are a good starting point for indicator development, it is recommended that the water input data are updated in the future to offer more temporal and spatial resolutions. These characterised water scarcity indicator results (using sub-national-level CFs) should be used by the avocado sector when communicating its environmental profile to external stakeholders. However, as water use on orchards is under the direct control of farmers, it may be more effective to use on-orchard volumetric water use as an indicator to support continuous improvement initiatives rather than (or in addition to) a characterised water scarcity indicator that includes indirect water use elsewhere in the supply chain (Sect. 5.1).

For ecotoxicity, there is a general lack of consensus about the proportion of pesticide emissions reaching different environmental compartments (air, water, soil, etc.) when modelling agricultural systems (Fantke 2019). The most widely used current approaches in agricultural LCAs base their models on the assumption that 100% of the applied pesticides (AIs) are emitted directly to agricultural soil (Nemecek and Schnetzer 2012; Christel et al. 2014; Fantke 2019; Nemecek et al. 2020), and this is the approach applied in this study. Also, agricultural soil is often not considered an environmental compartment for emissions (Birkved and Hauschild 2006; Christel et al. 2014; Rosenbaum et al. 2015) and so the fraction of pesticides that reaches, and remains in, agricultural soil is not assessed. It would be preferable in the future to update the ecotoxicity assessment to account for pesticide emission fractions reaching different environmental compartments and to include toxicity impacts in orchard soil as a separate indicator. Heavy metal emissions from fertiliser application should also be included.

Future studies could also consider other impacts relevant to perennial crop production identified in the literature, including acidification, biodiversity loss and agricultural land transformation (which is closely related to the soil carbon change impacts noted above). Novel impact categories could also be explored (e.g. inclusion of the nutritional aspect as an impact category) (McAuliffe et al. 2023; McLaren et al. 2021b). Finally, additional targeted data collection is recommended for any future avocado-related research in NZ. This includes data related to the 'source of origin' of fertilisers and agrichemicals used on NZ avocado orchards, as well as collecting soil conditioning data over several years which can then be used to calculate average annual inputs.

6 Conclusion

The NZ avocado sector has experienced robust growth in recent years and has significant potential for future growth driven by rising export demand. This could be enhanced by demonstrating its commitment to environmental sustainability through the use of LCA to determine its environmental impacts and identify improvements. The environmental hotspots identified in this research suggest the main areas of focus for improvement are fuel and fertiliser use for all impacts except water use, and additionally, agrichemical production for the ecotoxicity indicators.

The indicators measured in this study could be integrated into a future programme aimed at improving, and communicating, the environmental performance of avocado producers in New Zealand, and the aggregated regional and/or national values can be used as benchmarks. The study also highlighted a number of issues for further consideration when developing and using the indicators in this context, including use of a whole-of-life orchard perspective (including alternative functional units for different orchard lifespan stages), and incorporating eco-efficiency. Further methodological development is required for the ecotoxicity and water use indicators, in particular the use of more site-dependent, spatial and temporal impact modelling. Inventory data would be improved by collecting more detailed 'source-of-origin' data for fertilisers and agrichemicals. In addition, calculation of long-term carbon sequestration in orchard soils, trees, shelterbelts and infrastructure would provide a more holistic assessment of the climate change impact of avocado cultivation in NZ. Such refined indicators can support individual orchards to improve their environmental performance, while also communicating the environmental profile of NZ avocado production at the national and international levels.

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Data availability Information regarding primary input data and the rationale for selected data/calculation choices are available in the supplementary material attached along with this document. Additional data can be provided by the author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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