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Life Cycle-Based Environmental Methods and Indicators for Sustainable Consumption and Production in New Zealand Food Systems

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Executive Summary

The Sustainable Consumption and Production (SCP) approach requires considering the entire life cycle of a product – also known as life cycle thinking (LCT). Environmental Life Cycle Assessment (LCA) is one of the most widely used, internationally recognised, and standardised LCT-based SCP tools. The aim of this research therefore was to investigate how LCA can be used to support sustainable food systems, by applying it to both the production and consumption of food within a national context, in this case, New Zealand.

For the production-focused aspects of agri-food systems, the research focused on Voluntary Sustainability Standards (VSS) – a set of voluntary, predetermined standards with indicator-based criteria for use by agri-food producers. Most agri-food VSS criteria use practice-based rather than performance-based indicators, and they are mostly checkbox-type ones. Therefore, the first research question was, *‘What is the role of LCA in the development of performance-based indicators for VSS criteria for a New Zealand agri-food sector?’* The New Zealand avocado sector was used as a case study to address this question. A qualitative study was undertaken to explore the perceptions of stakeholders about the potential for a life cycle-based VSS for the sector (Chapter 2). Most respondents identified the need to quantify the environmental impacts of the avocado sector and supported use of a life cycle perspective. They noted the weak representation of environmental sustainability in the standard criteria of Global G.A.P., the only certification scheme used in the sector. Thus, in summary, they supported the introduction of a complementary scheme with science-based performance metrics and including the whole value chain.

An extensive LCA study was then undertaken for the orchard stage of the New Zealand avocado value chain (Chapter 3), to guide the development of indicators for facilitating continuous environmental improvement. Data were collected from 49 orchards across the three main growing regions in New Zealand, plus 4 orchards that were recently established and thus classified as being in the non-productive and low production years of the avocado orchard life

cycle. Individual orchard, regional and national level impact scores were calculated to use as benchmarks in indicator development, the latter two enabling growers to see their relative ranking in environmental performance at regional and national level. The impact results varied widely between the orchards across the three regions, and further research is needed to develop a better understanding of the reasons for this variability. The study also modelled the other stages of the orchards' life cycle, including the non-productive years of orchard creation, and the low-productive years during orchard establishment and senescence. The results from this model showed that the impacts increased by 13 to 26% per kg of avocados when including the low- and non-productive years of the orchard lifespan. Therefore, separate benchmarks using area-based functional units should be used for young orchards.

The system boundaries of the orchard-level study were then extended to include the post-harvest transport and packaging stage, as well as distribution to the first points of sale (PoS) in selected domestic markets and export markets in Australia and South Korea (Chapter 4). The orchard stage was the hotspot for all the scenarios with the exception of some of the airfreighting scenarios. The contribution of the post-harvest stages to total impact values across the scenarios was nevertheless noteworthy, ranging from an average of 41% and 22% of total supply chain impacts up to the overseas port for export avocados and up to the regional distribution centre (RDC) for domestic supply respectively. Thus, it is appropriate to include the post-harvest stages when developing LCA-based criteria for a VSS for the New Zealand avocado sector. Second, the study also showed that the packaging types used for international and domestic distribution have quite different environmental impacts. Therefore, in a VSS context, having two separate benchmarks for these two would be a more realistic approach than using a weighted average. Third, sensitivity analysis results showed that the average airfreighting impacts across different export scenarios for each impact category were 31-924% higher than the alternative shipping values. Thus, with respect to future marketing strategies of the New Zealand avocado sector (of which the main trend is to increasingly diversify into Asian markets), an indicator for a future VSS will be influenced less by market destination, and more by the

mode of transport used. It may be more useful to develop distribution-related benchmarks per unit of fruit transported over a set distance (for example, for climate change, kg CO₂ eq. per t.km) instead of using a distance-based weighted average per kg avocados. This could drive transport-related improvements like switching to slow shipping and electric vehicles, and optimising routes to reduce resource consumption and emissions. Lastly, sensitivity analysis also showed that extending the system boundary beyond the export port to retailers in Australia increased impacts, ranging from a 4% increase in water scarcity up to a 59% increase in terrestrial ecotoxicity. However, improvements in these downstream stages can only be instigated and monitored via a VSS if the stakeholders at the different stages represented in the VSS are cooperating together on this initiative. The New Zealand avocado sector stakeholders have more influence on the supply chain stages up to the export destination, but beyond this stage other stakeholders are more influential in terms of delivering environmental performance improvement with respect to these downstream activities. Therefore, it would be more feasible to maintain the system boundary to the port in terms of indicator development for a VSS for the avocado sector in New Zealand.

For the consumption-focused aspects of agri-food systems, nutritional LCA (nLCA) is a relatively new approach for conducting LCA studies where nutrition is considered the main, or one of the main functions of food. Thus, the second research question was, *‘What is the role of nLCA in helping New Zealand consumers make informed consumption decisions based on the combined nutritional value and environmental impacts of food?’* A study was conducted to investigate the development and potential application of an nLCA method to rank meals, using a case study of a ‘toppings on toast’ (ToTs) meal consumed in New Zealand (Chapter 5). Nutritional value was calculated using the NRF family of indices – specifically the NRF_{9.3} and NRF_{28.3} indices. A quartile-based method was used to assign weights to the NRF and climate change scores, which enabled ranking of the toppings. It was found that the rankings of the ToTs based on the nLCA results did not change much between the two indices. This suggests that the NRF_{9.3} index may be sufficient to determine overall the best, medium, and worst performing toppings in the ToT meal

context. However, the results also showed that water-soluble vitamins and unsaturated fats included in the NRF_{28.3} index contributed notably to the nutritional scores for most of the toppings and were instrumental in the rank changes for the toppings which are particularly rich in these nutrients. Thus, for a more diverse range of toppings/meals, an expanded index including these nutrients can generate more nuanced rankings.

General insights on VSS indicator development (Chapter 6) include the importance of including post-harvest stages; of conducting individual LCA studies for different agri-food sectors; of using non LCIA-based performance metrics for certain aspects like ecotoxicity assessment and airfreighting; and applying spatially disaggregated characterisation factors for water use. At the orchard stage, the importance of considering input and impact variability as well as the early and late years of the orchard were important factors for indicator development. At the post-harvest stage, the need for separate indicators and benchmarks for export and domestic packaging was noted, as well as the possibility of using impacts per t.km as an indicator for non-airfreight transport. At the consumption end, the need for updated nutrition intake data in New Zealand was highlighted. A nutritional index with fewer nutrients (but including mono and polyunsaturated fats) could be appropriate for practical application of the nLCA method in New Zealand. Further, nLCA results can be presented to consumers, based on both serve size and energy content, ideally via a graded label based on single scores or using a quantile-based colour-coded table if required by the consumer.

In summary, the research identified key considerations for use of LCA-based indicators and benchmarks in a VSS scheme to support the New Zealand avocado sector and linked these to the wider implications for agri-food production systems. For more sustainable food consumption, a new environmental rating methodology for alternative meals was developed based on nLCA, and its usefulness to consumers demonstrated using a case study of a toppings-on-toast meal in New Zealand. Thus, this thesis contributes to the agri-food SCP literature with respect to both method development and its application in New Zealand.

Acknowledgements

॥ वसुधैव कुटुम्बकम् ॥

The quote above is Sanskrit for 'The world is one family'. It is a simple philosophy in holism, one which fundamentally ties together all life on Earth in a web of interconnectedness that cannot be disregarded – either in a material or esoteric sense. It encompasses the very essence of sustainability.

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॥ कर्मण्येवाधिकारस्ते मा फलेषु कदाचन । मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि ॥

“You have the right to action but never to its fruits, let not the fruits of action be your motive, nor let your attachment be to inaction.”

~ Bhagavad Gita, Chapter 2 Verse 47

List of Abbreviations

10YFP	10 Year Framework of Programmes
AI	Active Ingredient
AWARE	Available WATER REmaining
BLF	Bulk Loose Fill
CF	Carbon Footprint
ED	Energy Density
EPD	Environmental Product Declaration
EPII	Estimated Prevalence of Inadequate Intake
FLW	Food Loss and Waste
FU	Functional Unit
GHG	Greenhouse Gas
IBI	Irregular Bearing Index
IQR	Inter-quartile Range
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LIM	Nutrient to Limit
LMIC	Low- and Middle-Income Country
MSI	Multi-stakeholder Initiative
MUFA	Monounsaturated Fatty Acid
NCD	Non-communicable Disease
nLCA	Nutritional LCA
NP	Nutritional Profile
NRF	Nutrient Rich Food
NRV	Nutrient Reference Value
NZFCDB	New Zealand Food Composition Database
PC	Plastic Crate
PCR	Product Category Rules
PoS	Point of Sale
PUFA	Polyunsaturated Fatty Acid
RDC	Regional Distribution Centre
RDI	Recommended Dietary Intake
SCP	Sustainable Consumption and Production
SDG	Sustainable Development Goal
SFS	Sustainable Food Systems
SLT	Single Layer Tray
TE	Tray Equivalent
ToT	Toppings on Toast
VSS	Voluntary Sustainability Standard
WF	Water Footprint

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Chapter 1 Introduction

“We have to change how we produce and consume food, not just for environmental reasons, but because this is an existential issue for humans.” ~ Janet Ranganathan, Vice-president for science and research at the World Resources Institute (WRI), December 2018

The global agri-food system is increasingly in the spotlight – not just because of the sustainability challenges associated with it, but also because it has potential for effective solutions to those very challenges as well (Ruggeri Laderchi et al., 2024). This thesis is concerned with some of those challenges in the context of New Zealand, and in particular with the application of environmental Life Cycle Assessment (LCA) to support decision-making in agri-food systems. This introductory chapter begins with an overview of the environmental and nutritional challenges facing agri-food systems today, and the global call for transitioning to Sustainable Food Systems (SFS) (Section 1.1). This is followed by an overview of the two topics central to this research: Sustainable Consumption and Production (SCP) (Section 1.2.1), and environmental LCA (Section 1.2.2). Sustainable consumption using nutritional LCA (nLCA), and sustainable production with LCA-based indicators in Voluntary Sustainability Standards (VSS) are then discussed in Sections 1.3 and 1.4 respectively. The relevance of this research to New Zealand is addressed in Section 1.5, followed by the research aim, questions, objectives, and conceptual framework for the research in Section 1.6. Finally, the thesis structure is represented in Section 1.7, followed by a list of the publications arising from the thesis (Section 1.8).

1.1 Sustainable food systems (SFS)

Food systems are inherently vast and complex networks of interconnected material flows, processes and actors/stakeholders involved in food production, processing, delivery, consumption and disposal (Nguyen, 2018) – developed for the overarching purpose of providing nutrition and food security for human societies (Heller et al., 2013; Porter et al., 2014). Sustainable food systems (SFS), on the other hand, are described as additionally being concerned that *‘the economic, social, cultural, and ecological bases to generate food security and*

nutrition for future generations are safeguarded' (Nguyen, 2018). An SFS must therefore be economically profitable, offer social (including nutritional) benefits and have a positive or neutral impact on the environment. However, current food systems are far from sustainable and are even considered by many to be 'broken', especially with respect to the integrity and quality of natural resources, impacts on the natural environment, and malnutrition which is becoming increasingly common in countries and societies worldwide (Osei-Owusu et al., 2022).

1.1.1 Environmental impacts of current agri-food systems

Foley et al. (2011) note that 70% of the world's total area in grassland, 45% of temperate, deciduous forest and 27% of tropical forest habitats have already been lost to agricultural production. Food systems overall contribute 25-42% of global anthropogenic greenhouse gas (GHG) emissions, with the agricultural production stage accounting for up to 86% of the total food system emissions (Crippa et al., 2021; Poore & Nemecek, 2018; Vermeulen et al., 2012). Moreover, agricultural production today is more expansive and resource-intensive, compared with traditional small-scale operations (Dudley & Alexander, 2017). Irrigation accounts for 70% of the total global freshwater extraction, making agriculture the world's largest water-consuming sector and contributing significantly to regional water stress on a global scale (FAO, 2021a; Mekonnen & Hoekstra, 2014). Nitrogen and phosphorous from fertiliser runoff causes eutrophication, resulting in hypoxia and killing aquatic organisms, thereby destroying biodiversity in freshwater and marine environments (Withers et al., 2014). Excessive use of generalist pesticides (killing all organisms indiscriminately) destroys beneficial organisms like pollinators along with the pests, impacting species biodiversity. At the same time, overuse of specialist pesticides (killing certain targeted organisms only) can cause the population of resistant targeted organisms to increase and result in damage to crops and biodiversity as well (Wainwright et al., 2014). Excessive use of agrichemicals and mineral fertilisers also result in heavy metal emissions (e.g. cadmium, zinc, copper, and lead), which can be extremely toxic to non-target organisms at higher trophic levels in the food chain (like mammals), due to bioaccumulation and biomagnification effects (Alengebawy et al., 2021). In addition, use of

synthetic fertilisers and agrichemicals can cause rapid physical, chemical, and biological degradation of agricultural soil (Ferreira et al., 2022; Hossain et al., 2020). In aquatic environments, aquaculture also contributes to effluent-related eutrophication, biodiversity loss due to conversion of marine and terrestrial land for aquaculture production, and further impacts on biodiversity when diseases are transmitted to wild fish stocks (Cao et al., 2013). Overfishing in the open seas – permitted by the growing capacity and global reach of fishing companies as well as the new technology available to them today has become the single largest driver of ocean biodiversity loss (Dulvy et al., 2021; Yan et al., 2021). Other environmental impacts driven by food systems also impact ocean biodiversity – for example, widespread coral bleaching due to warming oceans and marine pollution (Eddy et al., 2021).

Downstream food supply stages also contribute to environmental impacts. Packaging, for example accounted for 5.4% of the total GHG emissions from global food systems in 2015 (Crippa et al., 2021). Further, the impacts of food distribution are well documented, especially if transported over long distances by road or if using intensive modes of transport like air-freighting (see for example Bell & Horvath, 2020; Esteve-Llorens et al., 2022; Frankowska et al., 2019; Keyes et al., 2015). Food loss and food waste (FLW) is also an issue of global concern; on average, ~ 14% of food is lost during the different stages in a food product's supply chain (post-harvest transport, storage, processing, and distribution), and an additional 17% food wastage is attributed to the retail and consumption stages (FAO, 2019; United Nations, 2023a).

Thus transitioning to SFS requires cleaner food production and distribution practices with significant reduction in FLFW (Directorate-General for Research and Innovation (European Commission) & Group of Chief Scientific Advisors (European Commission), 2020; HLPE, 2020; Veldhuizen et al., 2020).

1.1.2 Nutritional challenges of current agri-food systems

Nutrition is a fundamental human requirement and right (HLPE, 2020). It is a unique and integral aspect of SFS, and some consider nutrition/health to be a separate and foundational

pillar of SFS, in addition to the environmental, social, and economic pillars of sustainability (Campbell & Feldpausch, 2023; Koerber et al., 2017; Nicholls & Drewnowski, 2021). However, current agri-food systems are related to significant nutritional challenges. Nearly 735 million people faced chronic hunger and a staggering 2.4 billion people did not have access to enough food in 2022 (United Nations, 2023a). There are 690 million undernourished people, and 11 million deaths related to poor diets around the world annually (Global Panel on Agriculture and Food Systems for Nutrition, 2020). Such diets are low in fresh fruits, vegetables, grains, nuts, legumes, milk, and seafood. They are also often characterised (particularly western diets) by red meat, processed and ultra-processed foods high in sodium, saturated/trans fats (such as grilled, salted and cured meats), and added sugar including sugar sweetened beverages (SSBs). All these factors result in the ‘double burden of malnutrition’¹ characterised by nutritional deficiencies on the one hand and overweight/obesity on the other hand (Grosso et al., 2020). Obesity and overweight affect 2 billion people globally resulting in 4 million deaths every year (Sabaté, 2019; Swinburn et al., 2019). Obesity and overweight are also closely related to losses in disability adjusted life years (DALYs), and preventable deaths due to Non-communicable Diseases (NCDs) such as Coronary Heart Disease (CHD), Type 2 diabetes, hypertension, strokes, and cancer (Clark et al., 2019; Global Nutrition Report, 2021; Springmann et al., 2018a,b).

The role of nutrition in SFS is represented in Sustainable Development Goal 2 (SDG 2)² (Zero Hunger), which aims to ‘*end hunger, achieve food security and improved nutrition and promote sustainable agriculture*’ (FAO, 2023; Jacob-John et al., 2021; United Nations Department of Economic and Social Affairs, 2024a). It is widely acknowledged that changes in consumption patterns and conscious dietary shifts (like reducing red meat consumption and moving to diets

¹ As per WHO (2024), ‘*Malnutrition, in all its forms, includes undernutrition (wasting, stunting, underweight), inadequate vitamins or minerals, overweight, obesity, and resulting diet-related non-communicable diseases (NCDs).*’

² The SDGs are a collection of 17 goals and 169 targets adopted by all UN member states in 2015 as part of the 2030 Agenda for Sustainable Development (United Nations Department of Economic and Social Affairs, 2015).

dominated by plant-based foods) towards ‘sustainable healthy diets’³, are not simply conducive to planetary and human health, but are actually necessary for transitioning to SFS (Clark et al., 2018; Rockström et al., 2020; Springmann et al., 2018b; Willett et al., 2019). Such transformational shifts require policy interventions and informed consumer choices (Ernststoff et al., 2020; Hallström et al., 2015; Heller et al., 2013; Meier & Christen, 2013; Notarnicola et al., 2017; Willett et al., 2019). However, the nutritional inadequacy of some of these diets is also an issue, especially with respect to micronutrients and bioavailability (Beal, 2024; Graham et al., 2019; Mazac et al., 2023)⁴.

This ‘diet-environment-health trilemma’ of global food systems (Clark et al., 2018) is a challenge for current and future food security, food sovereignty and resilience, and the sustainability of food systems (Berry et al., 2015; FAO et al., 2022). Moreover, the global human population reached 8 billion in 2022 – an increase of 5.5 billion people in just over 70 years. By 2050, it is expected to reach ~ 10 billion (Gu et al., 2021; United Nations, 2024b). To feed everyone sustainably in 2050, it is estimated that global food production overall will have to grow by >50% from current levels, while reducing GHG emissions by 67% and at the same time, curbing further land use change for agriculture and providing appropriate nutrition to everyone (FAO, 2021a; Ranganathan et al., 2018; Stratton et al., 2021; van Dijk et al., 2021). Thus, there is ample evidence that the situation requires urgent attention, and this has led to unanimous calls for a

³ Within the consumption context, FAO and WHO (2019) describe a sustainable healthy diet as one which contributes to the optimal growth and development of individuals, prevents all forms of malnutrition, reduces the risk of diet-related NCDs – one of the biggest food-related challenges of the 21st century – and preserves planetary health. According to the (Global Panel on Agriculture and Food Systems for Nutrition, 2020), transitioning to sustainable healthy diets could reduce GHG emissions by up to 74%, ‘*while boosting health, productivity, growth and resilience to climate shocks*’.

⁴ Nutrient bioavailability refers to the “*fraction of an ingested nutrient that becomes available for use and storage in the body*” (Melse-Boonstra, 2020). Bioavailability is an important aspect of nutritional studies because it explains how the consumption of a nutrient translates into actual health effects.

global transition to SFS (European Union, 2020; FAO & WHO, 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020; United Nations, 2023b; Willett et al., 2019).

1.2 Key topics

1.2.1 Sustainable consumption and production (SCP)

As noted in the call to action at the very first United Nations Food Systems Summit (UNFSS) (United Nations, 2021), a transition to SFS will involve a multi-pronged yet synergistic approach to food production and consumption – particularly, cleaner and resource-efficient production practices with minimal FLW, and sustainable consumption patterns that can ultimately provide nutritious food for all, with minimum environmental impacts (Von Braun et al., 2023). In essence, the SCP approach must be adopted to facilitate the transition to SFS (Li et al., 2022).

SCP first came to the attention of the international community in 1992, when the Rio Declaration explicitly introduced the SCP concept by urging states to *‘reduce and eliminate unsustainable patterns of production and consumption’* (United Nations, 2024a). Interest in SCP developed over the ensuing decades, and it formed the basis for Sustainable Development Goal 12: Responsible Consumption and Production. Resource efficiency lies at the heart of the SCP approach; its main aim is to decouple environmental degradation from socio-economic activities, while doing *‘more and better with less’* (Sonnemann & Margni, 2015; UNEP, 2010). This requires considering the entire life cycle of a product, from the point of product design, to obtaining and supplying raw materials, manufacturing, packaging and storage, distribution, consumption, and end-of-life treatment of resultant waste. life cycle thinking (LCT) – consideration of all the life cycle stages along the production-consumption spectrum (Life Cycle Initiative, 2012) – is therefore central to the SCP approach (One Planet Network, 2017; Sonnemann et al., 2018; Zu, 2013). The SCP approach can be implemented using several pathways (UNEP, 2010). For example, designing for sustainability entails consideration (during the design and planning phase) of sustainability along the product’s entire life cycle from raw material sourcing to end of life management, and is closely related to the circular economy paradigm. Cleaner production and sustainable transport look at low-impact and resource-

efficient production practices, transport of raw materials and distribution of products to consumers. Sustainable marketing, and lifestyles are more consumer-focused approaches and acknowledge the vital role consumer choice plays in driving life cycle sustainability. Eco-labelling and certification address cleaner production and sustainable consumer choices, and sustainable resource management is applied across the life cycle, especially in GSCM approaches. Lastly, waste valorisation and management practices address the sustainable management of the product at the end of its life cycle.

These concepts can be operationalised through:

- International policy: These include multilateral agreements and mechanisms – with the 2030 Agenda for Sustainable Development being the most widely adopted global agreement. Other examples include the Kyoto Protocol (UNFCCC, 2024b), the Clean Development Mechanism or CDM (Lo & Cong, 2022) and the Paris agreement (UNFCCC, 2024a). With respect to SCP specifically, the 10-Year Framework of Programmes (10Y FP) 2021 (One Planet Network, 2021; United Nations Economic and Social Council, 2023) appears as the very first target in SDG 12 (target 12.1), which requires that the programme be actioned by all countries via their national policy instruments.
- Regional/national policy: These include regulatory directives and policies at a regional or national level – for example the European Green Claims Directive to address the threat of greenwashing⁵, and green/sustainable public procurement or GPP/SPP employed by

⁵ Greenwashing is a phenomenon where companies strategically advertise their sustainability credentials via scientifically unsubstantiated and misleading wording or labels that exaggerate these credentials and hide their environmental externalities (Marrucci et al., 2022; Montero-Navarro et al., 2021; Muigua, 2023; Torelli et al., 2020). Existing greenwashing can drive consumers to make unsustainable choices due to misinformation, whereas the potential for greenwashing can further reduce consumer confidence in labelled products (including the more credible ones), thereby affecting their credibility, and their legitimacy and uptake (Gruère, 2013; Mori Junior et al., 2016). Although there is relatively lesser available research on agri-food greenwashing (compared to greenwashing overall in other sectors), it has frequently appeared in mass media as a legitimate challenge in the food industry (Montero-

governments in most developed nations⁶. The polluter pays principle (PPP) is a policy commonly applied in European legislation and other OECD countries, that requires that polluters to pay the negative externalities or cost of pollution (OECD, 1975; Pinto-Bazurco, 2022). Other examples include EU's Farm to Fork strategy (European Union, 2020) and the various national SCP policy frameworks like Vietnam's national action plan on SCP, New Zealand's emissions reduction plan, and India's new regulatory framework for its national non-agri-food eco-labelling scheme (FAO, 2020; Minister of Climate & MfE, 2022).

- Business approaches: Initiatives like tailored environmental strategies, business reporting like the Global Reporting Initiative (GRI), corporate target-setting initiatives like the Science-based Targets Initiative (SBTi), and management approaches such as Green Supply Chain Management (GSCM) and Life Cycle Management (LCM), and management tools/frameworks like Environmental Management Systems (EMS)⁷;

Navarro et al., 2021) and is considered a growing problem for sustainable food consumption today (BEUC, 2023; Changing Markets Foundation, 2023). The Green Claims Directive aims to protect consumers from the detrimental effects of greenwashing by banning generic and unsubstantiated (not supported by recognised fact-based proof of environmental excellence) green claims such as 'carbon neutral', 'eco-friendly', 'biodegradable', or 'natural' as well as ecolabels that are not approved by public authorities (European Parliament, 2023).

⁶ Historically public procurement has focussed on choosing the most economically viable products via tendering processes. However over time, sustainability considerations have featured increasingly prominently taking the form of GPP/SPP, and Voluntary Sustainability Standards (VSS)/ecolabels as well as life cycle considerations have become more embedded in GPP/SPP best practice policies to leverage governmental purchasing power for sustainability (European Commission et al., 2021; Neamtu & Dragos, 2015; Rainville, 2022; UNFSS et al., 2020). This applies to non-agri-food as well as agri-food products and catering services (EU Commission, 2019; FAO & Alliance of Biodiversity International and CIAT, 2021; Gómez-Ramos & Rico Gonzalez, 2023).

⁷ GSCM is the practice of applying and integrating environmental thinking into the management of product supply chains, i.e. reducing resource use, emissions, and waste along supply chains during product design, raw material sourcing, manufacturing, distribution and end-of-life management of the product (Chin et al., 2015). An EMS provides a framework for businesses to continuously improve their environmental performance via a 'Check, Act, Review, Improve' process – it is based on long-term strategic visions and employs short-term targets (Seidel-Sterzik, 2019).

- Multi-stakeholder Initiatives (MSIs): These involving government and private organisations, businesses, academia, and/or Civil Society Initiatives (CSOs) which facilitate SCP by research, advocacy, engaging stakeholders, raising awareness, and setting standards. A well-known example is the UNEP/SETAC Life Cycle Initiative (LCI)⁸. MSIs such as third-party verified assurance systems (like certifications and ecolabelling) are also widely acknowledged as a means to forward the SCP agenda.

Several of these pathways utilise quantitative analytical tools and methods, and one of the most common tools is environmental LCA.

1.2.2 Environmental LCA

The International Organization for Standardization (ISO) 14040 defines Environmental LCA as *'a technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study'* (ISO, 2006). Thus, LCA takes a cradle-to-grave approach in quantifying the environmental impacts associated with a product's entire life cycle from raw material extraction through to use and end-of-life fate. It is now one of the most widely used, internationally recognised, and standardised LCT-based environmental impact assessment tools. Since its conception, the LCA methodology has been significantly refined and employed in a variety of areas. Application areas include benchmark development (e.g. Cossu et al., 2023; Dias et al., 2017; Paratscha et al., 2019), establishment of performance indicators (e.g. Ghadimi et al., 2019;

LCM refers to practices related to the managerial decisions within an organisation or business for achieving improved sustainability performance using LCT, i.e. all the products, processes, and activities that are related to the organisation. An LCM or GSCM approach could therefore incorporate the use of an EMS or LCA as tools.

⁸ The UNEP/SETAC Life Cycle Initiative was launched in 2002 by United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) to foster and grow all knowledge and research related to LCT.

Heinonen et al., 2016; Repar et al., 2017), eco-design (e.g. Bianco et al., 2021; McAloone & Pigosso, 2018; Tao et al., 2018), and policy/legislation (e.g. Castellani et al., 2017; European Commission et al., 2021; Hélias et al., 2022). It has also been integrated in management approaches like green supply chain management (GSCM) and life cycle management (LCM) (Nilsson-Lindén et al., 2021; Pelton & Smith, 2015). More recently, novel methodologies have been developed such as dynamic LCA and nutritional LCA (Joliet, 2022; McLaren et al., 2021a; Mosquini et al., 2024). With respect to food systems in particular, LCA has been widely used to evaluate their environmental impacts along the production-consumption spectrum (e.g Clark et al., 2022; Dijkman et al., 2018; FAO, 2021; McAuliffe et al., 2018; McLaren et al., 2021a; Notarnicola et al., 2017; Salazar et al., 2019; Schaubroeck et al., 2018). It has been used at different scales from assessment of specific agri-food items (Notarnicola et al., 2015; Schaubroeck et al., 2018; Clark et al., 2022), to meals/menus (Schmidt Rivera et al., 2014; Calderón et al., 2018; Saxe et al., 2019; Takacs et al., 2022), to diets (Hallström et al., 2015; Aleksandrowicz et al., 2016; Eme et al., 2019; Batlle-Bayer et al., 2020; Henriksson et al., 2021). LCA is now acknowledged as the ‘reference method’ for determining supply chain environmental impacts of food overall (Sala et al., 2017).

As a ‘systems analysis’-based tool, an LCA study is bound by system boundaries and as per ISO guidelines, the LCA framework comprises four main phases (European Commission et al., 2010).

These four phases comprise:

- The Goal and Scope Definition: defining the main aim of the study and the functional unit (FU) (the unit of analysis which represents the function or service provided by a product system). The other steps include setting temporal and geographical boundaries, scoping the product system to outline the main activities and processes involved), choosing the modelling approach (attributional or consequential LCA), and deciding whether a peer review process is required.
- Life Cycle Inventory Analysis (LCI): involves collection of data with respect to the physical flows of inputs into and outputs (e.g. waste, emissions, by products).

- Life Cycle Impact Assessment (LCIA): this step comprises five sub-steps – Selection of impact categories and a representative indicator and environmental model for each impact category; classification of elementary flows from the life cycle inventory are assigned to impact categories; characterisation using environmental models quantify the impacts of the environmental flows, resulting in characterised scores for that impact category; normalisation of these characterised scores relative to a common set of reference impacts; and weighting the impacts across categories using ‘weighting factors’ that quantitatively shows the severity of an impact category in comparison with the others.

The last two steps allow impact scores across categories to be aggregated into a single score, which facilitates better and easier decision-making (Cucurachi et al., 2017). However, there is significant uncertainty (due to value judgements) associated with these steps.

- Interpretation: the results of the study are interpreted with respect to the goal and scope definition while acknowledging the limitations of the assumptions made in the first step (technological, temporal, geographical etc.)

All LCA phases are linked to one other, and thus it is an iterative process. All phases are revisited or modified throughout the assessment to ensure that the goal, scope and research questions are always addressed (European Commission et al., 2010).

The main strengths of LCA as an analytical tool are, firstly, identification of burden shifting – quantified impact trade-offs can be determined between different stages across a product’s life cycle, as well as between multiple impact categories (Klöppfer & Grahl, 2013). Secondly, LCA enables comparison between product systems and services (Hauschild et al., 2018). On the other hand, shortcomings of LCA include: 1) it is a heavily time and resource-intensive process; 2) uncertainty is intrinsic to LCA as there can be various sources of uncertainty at different stages of the LCA. This can be due to temporal, spatial, and in-object variability in data. Uncertainty can also result from data input parameters which can occur at all levels – in the raw data, the LCI phase, and characterisation model, and from methodological choices; 3) LCA

methods do not include risks associated with industrial accidents, nuclear power or sudden environmental disasters like oil spills (Bjørn et al., 2018; Paulillo et al., 2020); 4) LCA does not allow for assessments of all environmental impacts such as those resulting from antibiotic production and use and plastics/microplastics (Nyberg et al., 2021; Satta et al., 2024; Schwarz et al., 2024); 5) there are regional and temporal limitations to LCA impact analysis; 6) the results of an LCA can be challenging to communicate to a wider audience.

1.3 Sustainable consumption and nutritional LCA (nLCA)

Information provision to inform consumer choices is an important element in achieving SCP. This is reflected in SDG target 12.8 which aims to *‘By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature’* (Gasper et al., 2019). Research over the last 20 years has shown that nutritional labelling can facilitate and encourage healthier food choices (Brown et al., 2020), and nutrition labels are used on packaged foods to help consumers make more informed and healthier food choices (Hodgkins et al., 2015). In fact, a food item’s nutritional value in terms of certain specific nutrients (such as carbohydrates, sugars, dietary fibre, and salt) is mandated by most governments as ‘back-of pack’ declarative information panels (e.g. Nutrition Facts Panel in the USA, Nutrition Information Panel in Australia and New Zealand (FSANZ, 2023; Hieke & Harris, 2016). In addition, more recently there has been increasing use of voluntary ‘front-of-pack’ labels, which provide more simplistic ‘at-a-glance’ information for consumers to interpret nutritional information and make decision-making easier (UNICEF, 2022; Wartella et al., 2010).

Several studies have shown consumer preferences for environmentally sustainable foods, when trustworthy ecolabels are available to communicate those credentials to them (e.g. Gow et al., 2022; Holenweger et al., 2023; Kühne et al., 2023; Testa et al., 2015). Examples of food ecolabels include the Swiss Eaternity score, France’s Planet-Score and Eco-Score labels, the non-profit Foundation Earth’s Eco-Impact label, and Enviroscore developed by AZTI and KU Leuven (Boone et al., 2023; De Bauw et al., 2022; Planet Score, 2022). These labels are based on LCA studies, and aggregate impact values across multiple impact categories into a single score (via

normalisation and weighting), which is then translated into a final front-of-pack “traffic light” label where sustainability is expressed in traffic light colours – red, amber, green, with red most unfavourable and green the most optimal choice, based on the criteria established for that label (WBSCD, 2021).

Consumers can be significantly supported in their choices for healthy and sustainable foods by having access to easily comprehensible information about a food product’s environmental and nutritional credentials in the form of indicators and other science-based metrics (Notarnicola et al., 2015, 2017). Some research attention has been directed at combining environmental and nutritional information (Grigoriadis et al., 2021) and using such combined information for sustainable food labelling (Bunge et al., 2021). However, no such combined label has been applied yet to food products sold in retail outlets.

Food LCAs have traditionally mostly used mass- or volume-based FUs, and do not account for nutritional value (Saarinen et al., 2017; Sala et al., 2017; Sonesson et al., 2017). Yet one of the most critical functions of food is to provide nutrition to support healthy growth, development, and longevity (Willett et al., 2019; World Health Organization (WHO), 2023). This has led to the development of a nascent field of study known as nutritional LCA (nLCA), defined as an LCA study in which nutrition is considered the main, or one of the main, functions of food (McLaren et al., 2021a). nLCA as a research area has attracted much attention in recent years and new methodologies are constantly being developed to incorporate nutritional and environmental parameters using the life cycle approach. Moreover, combined nutritional and LCA studies have mostly focused on individual food items or diets; there have been relatively fewer combined studies at the meal level, particularly within a national level context⁹. Thus, there is not only opportunity, but also potential for further methodological development in nLCA as an SCP approach to sustainability by providing combined nutritional and environmental life-cycle based information to inform consumers at several levels of food-related decision-making.

⁹ For a more comprehensive review of literature on this topic, please see Chapter 5.

1.4 Sustainable production and LCA in Voluntary Sustainability Standards (VSS)

This section introduces VSS, the types of indicators used in agri-food VSS and the inclusion of LCA-based metrics in these indicators, the importance of LCA-based benchmarks, and an overview of the main VSS-related research themes demonstrating the main life cycle-related gaps within this body of research.

1.4.1 Introduction to VSS

VSS are defined as *'standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics, including respect for basic human rights, worker health and safety, the environmental impacts of production, community relations, land use planning and others'* (UNFSS, 2012). Agri-food VSS usually have associated ecolabels which demonstrate the sustainability credentials of the food product. While these ecolabels provide information to the consumer to inform consumption choices, the standards are primarily directed at encouraging more sustainable practices in the production and supply of these products. Thus, they are more aligned to the production end of the SCP approach. Agri-food VSS have been consistently growing in type and number since the 1990s and have especially proliferated in the last decade (Tayleur et al., 2018; UNFSS et al., 2020). Table 1.1 outlines the mainstream third party certified agri-food and forestry VSS, and the product sectors they cover (See Appendix A, Table A1 for more details on these VSS).

Table 1.1 Examples of mainstream agri-food VSS (Source: Individual standard websites and ITC, 2023)

Food Category	Sectoral Application	Name of VSS	Geographic Scope*
Horticulture	Sugarcane, sugar, ethanol	Bonsucro	International
	Cotton	Better Cotton Initiative (BCI) Cotton Made in Africa (CMiA)	International Regional
	Oil Palm	Roundtable on Sustainable Palm Oil	International
	Coffee	The Common Code for the Coffee Community – 4C	International
	Soy	Roundtable on Responsible Soy (RTRS)	International
	Multiple	Rainforest Alliance Fairtrade Proterra	International International International
Aquaculture/Fisheries	Seafood	Marine Stewardship Council (MSC) Aquaculture Stewardship Council (ASC) Global Seafood Alliance Best Aquaculture Practices (BAP) Friend of the Sea marine aquaculture	International International International International
Viticulture	Grape and wine	Sustainable Winegrowing New Zealand (SWNZ) California Sustainable Winegrowing Alliance (CSWA) Equalitas V.I.V.A. Sustainable Wine South Africa (uses the Integrated Production of Wine (IPW) South Africa standard) Sustainable Winegrowing Australia (uses the Australian Wine Industry Standards of Sustainable Practice for Viticulture and Winery)	National (New Zealand) Regional (California) National (Italy) National (Italy) National (South Africa) National (Australia)
Others	Multiple sectors (Dairy/meat/poultry/floriculture/arable crops) (Organic)	Red Tractor LEAF Marque Sustainable Rice Platform Unilever Sustainable Agriculture Code Origin Green	National (U.K.) International International International National (Ireland)

		Global G.A.P Country-level G.A.P. schemes (e.g. PhilGAP, ThaiGAP, QGAP, NZGAP, Freshcare, SwissGAP etc.) Food Alliance African Organisation for Standardisation (ARSO) Protected Harvest	International National (multiple) National (USA) Regional (Africa) National (USA)
Others	Multiple sectors (Dairy/meat/poultry/floriculture/arable crops) (Organic)	IFOAM Organics USDA Organic Biogro NZ Pacific organic aquaculture Naturland organic aquaculture National Programme for Organic Production (NPOP)	International International (USDA) National (New Zealand) Regional (Pacific countries) International National (India)

**Refers to the geography of the produce that the VSS is applied to – not the country of origin of the VSS or its headquarters*

Most of the VSS mentioned in Table 1.1 are sector-specific, i.e. the standards apply to a single sector. Several generic VSS umbrella programmes which cover multiple sectors also have specific sectoral standards, for example, Origin Green has standalone standards for dairy, beef, poultry, and horticulture, while ASC has standards for different aquatic species like salmon, bivalves, and flatfish. Such sector-based approaches to sustainability can be particularly effective because the unique characteristics of each sector are taken into consideration, which makes it more relevant than a generic one. This is especially true in the case of agri-food systems, given the considerable variability between sectors in terms of multiple factors such as climate, geography, and production systems.

1.4.2 Environmental indicators in VSS criteria

An indicator can generally be defined as *‘a variable or combination of variables collected and analysed with a well-defined analytical or policy goal, and for which certain reference values are significant in the context of the analysed system’* (Avadí & Fréon, 2015). Generally, sustainability indicators are characterised into three main typologies: practice-, target-, and performance-based (FAO, 2014). Practice-based indicators, also known as process- or technology-based indicators, are checkbox-type and require yes/no answers to assess whether certain technologies or processes are being implemented (e.g. *‘Organic waste material should be composted and used for soil conditioning’*). Target-based indicators are also prescriptive – they require that certain management plans be put into place, with associated targets that must be achieved over a certain period of time (e.g. *‘A documented plan on identifying opportunities to improve energy efficiency shall be available, multi-year if necessary’*). Performance-based indicators on the other hand, are verifiable metrics (e.g. *‘Report water use for irrigation in total and per unit of product (L, L/kg)’*). Thus, they progress the ‘sustainability via measurement’ approach, by providing growers with quantitative feedback about their environmental performance, which they can then use to improve their practices on a continuous basis (Freidberg, 2017; Hatanaka et al., 2022; Konefal et al., 2022; Merli et al., 2018; Veale et al., 2015). Such metric-based indicators of farm-level sustainability performance can thus effectively

facilitate continuous improvement¹⁵, since quantitative baselines can be ascertained, data collected and analysed, and actions can be taken to improve those baselines constantly. They have therefore become increasingly common as a means of agri-food sustainability governance (Hatanaka et al., 2022). However, agri-food VSS generally use practice- and target-based indicators (Bush et al., 2013; Hatanaka et al., 2022; Konefal et al., 2022; McGarr-O'Brien et al., 2023). It is also important to note that agri-food VSS never include indicators addressing nutritional aspects as the subject of nutrition has been traditionally oriented towards food consumption.

As shown in Table A1 in Appendix A, only six VSS-based schemes use LCA-based performance indicators (see Chapter 4 for more details). These indicators mostly cover the growing/farm stage of the life cycle, and omit downstream stages like packaging, distribution, retail, transport, and consumption (except the wine VSS which include the winery stage). There are also no indicators for upstream stages like nursery activities or orchard establishment and development, which can be important contributors to whole of life impacts of food production (Basset-Mens et al., 2016; Bessou et al., 2013, 2016; Cambria & Pierangeli, 2012; Cerutti et al., 2014; Nicese & Lazzerini, 2012; Lazzerini et al., 2014). Moreover, the VSS indicators do not take variability into account with respect to farm conditions (for example, temporal, geographic, or climatic settings as well as differences in managerial practices). Lastly, they are almost entirely focused on GHG emissions and carbon footprints (CFs). Only one VSS – the V.I.V.A. wine scheme has an LCA-based criterion for water use in addition to a CF.

With respect to the LCA-based GHG indicators, the standards either use their own bespoke CF calculators (for example the Bonsucro calculator, Origin Green's Carbon Navigator, and RSPO's PalmGHG calculator), or other recommended industry tools like U.K's Cool Farm tool. Most of these tools follow relevant international standards like PAS 2050:2008, ISO 14067:2018, ISO 14040:2006, ISO 14044:2006, and/or the GHG Protocol Accounting and Reporting standard for calculating Scope 1,2, and 3 emissions.

1.4.3 Benchmarking in agri-food VSS

The data obtained from performance-based indicators can be used as feedback to growers for benchmarking purposes (Bord Bia, 2013, 2017; Lees, 2020; Viart et al., 2016). Benchmarking is the process of comparing an entity's products, services, processes, and performance against a reference value. It is now widely acknowledged as a facilitator for continuous performance improvement across industries and sectors, including agriculture (Gasso et al., 2025). Benchmarking can be internal to an organisation or external, i.e. using an external entity as the reference. Given the multiple contexts in which benchmarking can be used, it can be defined in several ways (Galindro et al 2019). Sometimes benchmarking in a VSS takes the threshold approach, i.e. the absolute benchmark which an entity needs to meet to obtain certification. However, most of the LCA-based metrics used in agri-food VSS are relative benchmarks, i.e. are used to communicate information about performance relative to previous years for an individual entity, or relative to the sector average performance. Bonsucro is the only VSS from the surveyed schemes that uses LCIA values as thresholds to be met in its environmental criteria (Veale et al., 2015). In addition, the new ASC farm standard which is currently undergoing public consultation and will be operational in 2025, defines species-specific GHG values as upper threshold benchmarks (ASC, 2024). Once operational, farmers will be expected to take actions to keep their emissions under the threshold and continuously improve on them year-on-year.

1.4.4 Summary of current research themes in agri-food VSS

Given the profusion of VSS in recent decades and their potential to drive change, there has been abundant scholarly research into various aspects of VSS, with copious amounts of literature now available across disciplines (Marx et al., 2022). There are three main threads of academic research pertaining to VSS:

- The emergence of VSS as a significant Non-State Market Driven (NSMD) sustainability governance mechanism (e.g. Auld, 2010; Auld et al., 2008; Cashore et al., 2015; Cashore et al., 2004; Gulbrandsen, 2009);

- The institutional design of VSS (e.g. Auld & Bull, 2003; Fiorini et al., 2019; Marx, 2013). Research has focused on governance aspects (Mori Junior et al., 2015; Ponte & Cheyns, 2013), including interactions between stakeholders and actors (e.g. Fuchs et al., 2011; Lambin & Thorlakson, 2018); standard-setting processes (e.g. Boström & Hallström, 2013; Sustainable Biomass Programme, 2020; van der Ven, 2022; von Geibler, 2013); and the application of the principles of legitimacy, transparency, credibility, and accountability in VSS (e.g. Auld & Gulbrandsen, 2010, 2014; Bernstein & Cashore, 2007; Bush et al., 2013; Cashore, 2002; Haack & Rasche, 2021; Hatanaka & Konefal, 2013; Marx, 2013; Schleifer et al., 2019; Schouten et al., 2022; Schouten & Glasbergen, 2011);
- The success of existing VSS. Research has focused on the enablers of and barriers to the uptake of these schemes (e.g. the role of retailers in driving VSS development and uptake (Fuchs et al., 2011; Lockie et al., 2015; Masood, 2015; van der Kloet, 2011)), and the diffusion and effectiveness of VSS in facilitating sustainability (e.g. Amundsen et al., 2019; Andersson & Hammarlund, 2023; Arton et al., 2020; Auld et al., 2008). The social and economic impacts of VSS on smallholders in the Global South has also been investigated (Akrong et al., 2022; DeFries et al., 2017; Dietz et al., 2021; Loconto & Dankers, 2014; Meemken, 2020; Oosterveer et al., 2014).

In addition, VSS have been evaluated with respect to various other miscellaneous themes including: their role in transnational trade and policies (Bernstein & Cashore, 2012; Foley, 2017); the role of the state in - and its interaction with - VSS (Abbott & Snidal, 2008; Abrams et al., 2018; Burns et al., 2016; Gale & Haward, 2011; Giessen et al., 2016; van der Ven & Barmes, 2023); their contribution to food security in particular (Oosterveer et al., 2014; Schleifer & Sun, 2020) and to the SDGs overall (Bissinger et al., 2020; Schleifer et al., 2022; UNFSS et al., 2020); and their importance in developing economies (Negi et al., 2020).

Among all the research reviewed, only three studies were identified which assessed representation of LCA in agri-food VSS. Firstly, Mungkung et al. (2006) investigated how LCA can be used to develop criteria for a potential ecolabelling scheme in the Thai shrimp sector. This

study was conducted within the context of the ISO type 1 ecolabel¹⁰ criteria development processes, i.e. using LCA to determine the relevant impact categories and life cycle stage hotspots in the product life cycle, which could then potentially inform ecolabel criteria development. It did not discuss the use of LCIA values as metrics to be used as benchmarks within the standard criteria. Moreover, the study included all stages of the Thai shrimp life cycle and found the shrimp farming stage to be the environmental hotspot, and therefore only focused on the farming stage when discussing potential indicators. Further, the sample size was limited – only one farm representing conventional shrimp production was studied. Thus, the study did not consider the variability of production systems, which is an important factor identified by sustainability assessments of primary production systems (Cerutti et al., 2014; Gasso et al., 2025; Lam et al., 2021; McLaren et al., 2021b; Pelletier, 2017; Poore & Nemecek, 2018).

Mohan (2018) used a cradle-to-farm gate LCA to inform the development of indicators for a potential farm-based environmental certification scheme for sheep milk in New Zealand. The LCA study showed the environmental hotspots in the sheep milk production system, and these learnings were then used to inform the development of prototype lists of qualitative indicators based on a study of four existing certification schemes. Thus, this study looked into the development of practice-based indicators only (except for the requirement of a CF calculation). Moreover, this study was limited to the farm gate and excluded downstream stages of the sheep milk life cycle. Also, the study only looked at one agri-business and did not consider the

¹⁰ As per the ecolabelling and declaration principles laid out in ISO 14020:2000, product-based labels are traditionally classified as ISO Type I (ISO 14024:2018), Type II (ISO 14021:2016) and Type III (ISO 14025:2006) labels (ISO, 2019, 2022). Of these, ISO type 1 ecolabels are based on LC considerations, but do not require a full LCA study to be conducted; and type 3 labels are actually declarations like Environmental Product Declarations (EPDs) which use full LCA studies to describe a product's environmental impacts quantitatively (Kietzmann, 2024). Agri-food VSS cannot be characterised by the ISO typology framework, but they are most similar to type 1 labels. Therefore they are also called Type 1-like ecolabels (Horne, 2009; Panainte et al., 2014; Prieto-Sandoval et al., 2016; UNEP, 2024).

variability inherent in multiple farming systems across different geographies and management practices.

In a third paper, Cossu et al. (2023) attempted to demonstrate how the Made Green in Italy scheme (which is LCA-based but not been applied to fresh food products yet) could be potentially applied to hard sheep milk cheese. They used LCA-based impact values to develop three performance classes between upper and lower performance thresholds. The relative benchmark value was the median between the two values. This was the only study that investigated the idea of LCIA-based values as benchmarks and thresholds in VSS criteria. It did not, however, develop individual values for different impact categories. Instead, this study used normalisation and weighting to arrive at a single score to develop ranges of performance classes into which products could potentially be categorised. Furthermore, the study looked at four dairy farms in one region of Italy and did not discuss the implications of variability in production systems across different geographies, climates, and practices.

As mentioned earlier, environmental LCA is a holistic approach. Consideration of life cycle stages other than just the production stage and assessment of multiple environmental impacts instead of focusing on just one (in this case, climate change) is necessary to avoid burden shifting. Moreover, variability between farms/orchards, their productivity and yields, their geographic, soil, and climatic conditions, and the differences in resource availability at these different locations can result in highly variable input and impact values. This variability needs to be appropriately considered when developing indicator systems with metric-based benchmarks, so that they are more nuanced and sensitive to local/regional contexts and therefore more suited for effective actions (Gasso et al., 2025). McLaren et al. (2021b) also note the importance of taking this variability into account and add that variability of other factors like the orchard age, yields between years, and orchard management practices must also be considered, especially in the case of perennial crops.

Thus, there is merit in addressing these research gaps, by exploring the factors related to, and the approaches that can be taken in developing LCA-based metrics for use as performance

indicators and benchmarks for criteria in VSS for agri-food sectors. In particular, the research to date suggests three main focus points: 1) inclusion of indicators based on other impact categories in addition to climate change; 2) inclusion of downstream stages of the product life cycle; and 3) consideration of variability in production systems.

1.5 Relevance of research to support SCP for New Zealand

In their report on SDGs, Sachs et al. (2025) provide country-level dashboards showing progress in terms of whether the SDG has been achieved, and if not, what level of challenges remain (major, significant, minor) and how the country is progressing towards achieving those SDGs (decreasing, improving, stagnating). According to the report, New Zealand is trailing behind on progress towards meeting several SDGs especially the agriculture, nutrition, and environment-related ones. These are SDGs 2 (Zero Hunger), 13 (Climate Action), 14 (Life below Water), and 15 (Life on Land) (Sachs et al., 2024). SDG 12 (Responsible Consumption and Production) applies to multiple goals and also faces major challenges, with progress towards the goal stagnating.

Regarding SDG 2, the average New Zealand diet (like most Western developed countries) is abundant in ultra-processed and discretionary foods rich in added sugar, salt and red meat, and this (along with sedentary lifestyles) has contributed to a rise in obesity, NCDs and related mortality (Mackay et al., 2022; Starck et al., 2021). Further, the climate and land use impacts of conventional agriculture, as well as its polluting effects on New Zealand's freshwater systems, have been of increasing concern with respect to SDGs 13, 14, and 15 (MfE, 2023; Palliser et al., 2019). Particularly with respect to SDG 13, although New Zealand has made more progress than the other four environmental SDGs mentioned, there is still some way to go to meet the national targets¹¹. For example, New Zealand's total GHG emissions in 2022 were 78.4 Mt CO₂ eq. –

¹¹ As part of its national targets, New Zealand aims to reach net zero GHG emissions (other than biogenic methane) by 2050, with total emissions no more than 290 megatonnes between 2022-2025 and 305 megatonnes from 2026 to 2030 (MfE, 2024b).

agriculture contributed to 53% to this total, with most of it attributed to methane emissions from the beef and dairy sectors (MfE, 2024a).

Regarding SDG 12, the first target (target 12.1) requires that developed countries lead the way in actioning SCP programmes (One Planet Network, 2024; United Nations Department of Economic and Social Affairs, 2024b)¹². This is because developed countries are more equipped than developing countries to facilitate the required changes as they have the economic infrastructure and capabilities (United Nations Department of Economic and Social Affairs, 2024b; Wang et al., 2019). Also, developed countries' demand for goods and services (and concomitant consumption-related impacts) far supersede developing countries, despite having a relatively small proportion of the global population (only 20% of the world's population resides in developed countries)¹³ (Tukker et al., 2008). However, as a developed country, New Zealand's stagnation on the progress towards SDG 12 (see Figure 1.4) is concerning and needs concerted action.

Secondly, New Zealand's economy is characterised by its export-driven primary agri-food industry sectors (dairy, meat and wool, forestry, and horticulture). This presents the New Zealand agri-food industry with not just strategic positioning for a sustainable future, but also significant opportunity to effect the transition to SFS (Bardsley et al., 2020). Furthermore, New Zealand is recognised internationally for its 'clean green' and '100% Pure' image, which draws not only from the country's extensive natural resources and beauty, but also on its historic

¹² The 10YFP aims to operationalise sustainability via six thematic pathways – three of these are sectoral (sustainable buildings and construction, food systems, and public procurement), while the other three have cross-cutting agendas (consumer information for SCP, sustainable lifestyles and education, and sustainable tourism) (One Planet Network, 2022). Thus, within the 10YFP framework, SCP can be operationalised in agri-food systems via the food systems thematic pathway and the two consumption-related cross cutting pathways – consumer information and sustainable lifestyles/education.

¹³ According to United Nations (2023a), the per capita material consumption of developed countries is 10 times that of developing countries, which are typically Low and Middle Income Countries (LMICs).

commitment to conservation and environmental sustainability (Abbott et al., 2018). The Green Growth Advisory Group (2011) stated that this image was truly the ‘cornerstone’ of the country’s brand identity and recommended that the New Zealand story be articulated to stakeholders across the board as a *‘fact-based narrative about New Zealand’s place in the world as a competitive trading nation with comparatively strong green credentials’*. New Zealand’s clean green image has been critical to product differentiation and marketability and has helped several industry sectors to make their products more profitable in export markets – including its agri-food sectors (Blackett & Le Heron, 2008; Foote et al., 2015; Stenton-Dozey et al., 2021). Pure Advantage (2012) called attention to the fact that no other country in the world is as reliant on its clean green image for its exports as New Zealand and as such, it should be leading the green growth race.

However, the Parliamentary Commissioner for the Environment (2002) cautioned over two decades ago that *‘New Zealand’s image as a clean and green place will have to be earned in the future’*. By 2012, the international community had already stopped considering New Zealand an environmental leader with respect to carbon emissions, and concerns were raised regarding the disconnect between the country’s clean green image and its environmental realities (Kaefer, 2014), including those related to climate change, and marine and freshwater pollution (Ulrich & Handley, 2020). Today, sustainability credentials are no longer regarded an optional ‘add-on’ for agri-food businesses but are recognised as an essential part of business. This is evidenced in the business strategies of large agri-food manufacturers like Kellogg’s, Cargill, Unilever, and Nestle as well as retailers such as Woolworth’s, Tesco, Walmart, Albertsons, and Krogers (Bloom, 2015; Czarnecki, 2011; Hatanaka et al., 2022; Thorlakson et al., 2018). MPI (2023) has noted that in the future sustainability will become more of a standard than a differentiating factor – it will be an intrinsic part of business-as-usual. Thus, developing a credible New Zealand sustainability brand and telling the New Zealand sustainability story will be crucial to the primary sector going forward (MPI, 2023).

1.6 Research aim, questions and objectives

As discussed in Sections 1.1 to 1.5, current agri-food systems face significant environmental and nutritional challenges and a transition to SFS is required to meet and overcome these challenges. An SCP approach (which inherently includes life cycle thinking and associated tools like LCA) to SFS should be taken in order to ensure cleaner (less environmentally harmful) food production/supply and enable sustainable decision-making with respect to food consumption to encourage more healthy diets. At the production end, VSS are widely adopted to enable cleaner agri-food production systems. However, current agri-food VSS generally do not include performance-based metrics, especially those based on life cycle considerations. This lack of evidence-based metrics reflects an inherent inadequacy within VSS to effectively measure and track the environmental performance of food products along the life cycle and thereby guide industry change. Moreover, at the consumption end, no combined life cycle-based environmental and nutritional indicators have been developed so far to help consumers make informed food consumption decisions, especially at the meal level. This research addresses both these gaps using LCA as the common framework. Furthermore, New Zealand is well-positioned for this research because its primary sector is an important part of the economy, it has some way to go in achieving the SDGs, and it has an economic motivation to demonstrate longstanding national 'clean, green' image. The overall aim of this thesis therefore is 'to investigate the use of LCA-based approaches for more sustainable agri-food production and consumption in New Zealand'.

As mentioned in Section 1.4.1, there is merit in adopting voluntary, sector-based approaches compared to generic ones (Dodds et al., 2013); their benefits include administrative ease, more efficient data collection/management, reputational advantages, and knowledge sharing (Seidel-

Sterzik et al., 2018). Therefore, it was decided to focus on the New Zealand avocado sector¹⁴ as a case study, and the following research questions were defined:

- Research Question 1 (RQ1): What is the role of LCA in the development of performance-based indicators for VSS criteria for a New Zealand agri-food sector?
- Research Question 2 (RQ2): What is the role of nLCA in helping New Zealand consumers make informed consumption decisions based on the combined nutritional value and environmental impacts of food?

The associated research objectives (ROs) are:

- RO1: To identify potential enablers and barriers to an LCA-based VSS in the New Zealand avocado sector
- RO2: To conduct an LCA study to guide the development of indicators and benchmarks for continuous improvement in the environmental performance of New Zealand avocado orchards
- RO3: To conduct an LCA study of the downstream stages of the New Zealand avocado supply chains, and associated development of indicators and benchmarks for continuous improvement in a VSS context

¹⁴ During discussions prior to embarking on the research, the New Zealand avocado industry sector association was motivated to understand their environmental impacts and keen on LCA-based data. This informed the decision to further investigate the sector's readiness and motivation, and a qualitative study was conducted to determine the potential enablers of and barriers to a life cycle-based certification scheme in the avocado sector (Chapter 2). The study showed that stakeholders in the New Zealand avocado value chain were proactive about environmental initiatives; they were open to the idea of a sector-based environmental certification scheme or VSS; they were aware of the lack of science-based quantitative data on the environmental impacts of the sector and highlighted this as a requirement for any environmental certification scheme or monitoring programme; and they favoured taking a life cycle perspective when developing a potential certification programme. For further details on the justification for using the New Zealand avocado sector as a case study, please see Chapter 2.

- R04: To develop an nLCA method to help consumers make environmentally and nutritionally informed choices within the meal context.

The conceptual positioning of this research along with the RQs and ROs, is shown in Figure 1.1.

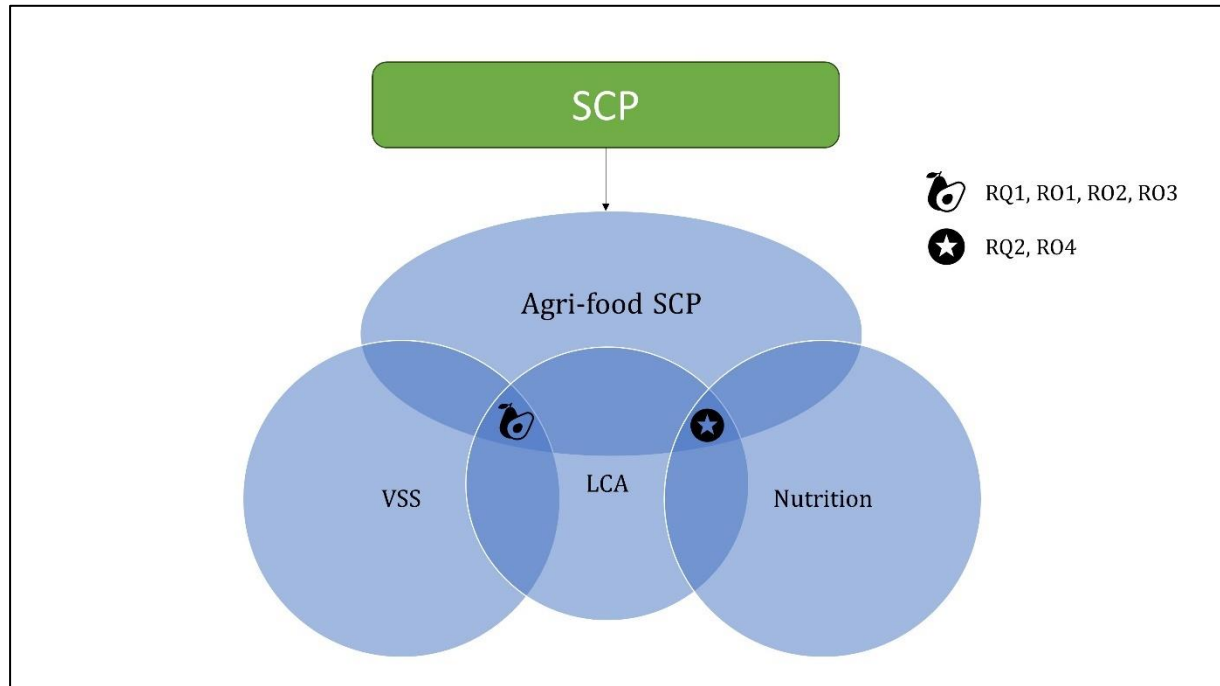


Figure 1.1 Conceptual positioning of the PhD research (including RQs and ROs)

1.7 Thesis structure

Figure 1.2 shows the thesis structure in the context of the conceptual positioning of the research.

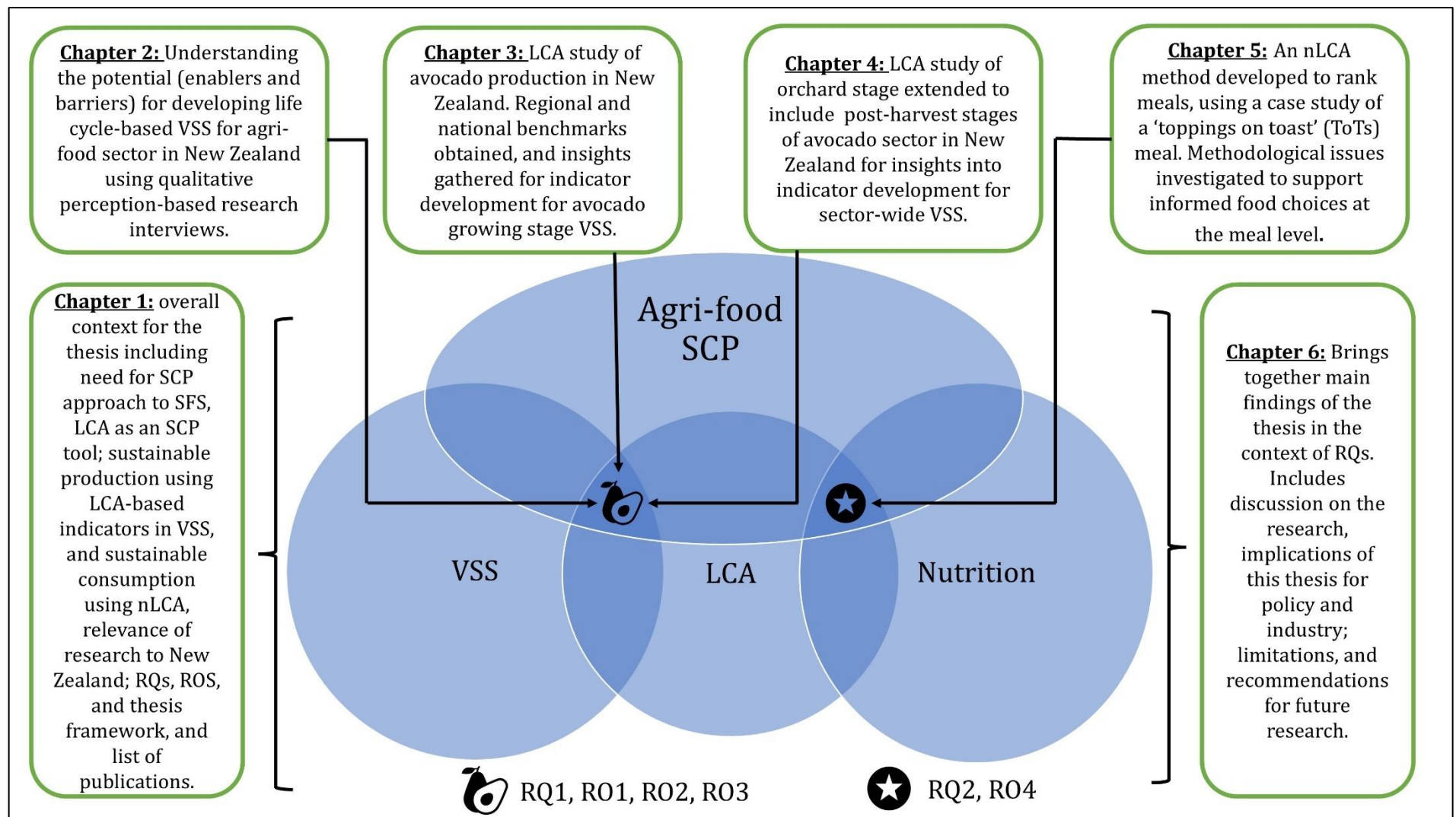


Figure 1.2 Thesis structure in the context of conceptual positioning of research

1.8 Publications arising from thesis

The peer-reviewed publications/presentations arising from this research are:

- 1) Majumdar, S., & McLaren, S.J. (2023). Towards use of life cycle-based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand. *The International Journal of Life Cycle Assessment*. 29, 192-217. <https://doi.org/10.1007/s11367-023-02238-x> (Chapter 3)
- 2) Majumdar, S., McLaren S.J., van der Pols, J.C., and Lister, C.E. (2024). An nLCA approach to support consumer meal decisions: a New Zealand case study of toppings on toast. *Frontiers in Sustainable Food Systems*. 8:1363565. <https://doi.org/10.3389/fsufs.2024.1363565> (Chapter 5)
- 3) Majumdar, S., and McLaren, S.J. Life cycle-based environmental indicators in agri-food Voluntary Sustainability Standards: case study of New Zealand avocado post-harvest activities. Being drafted for journal submission. (Chapter 4)
- 4) Majumdar, S., Garnevska, E., & McLaren, S.J. Potential for a life cycle-based VSS in the New Zealand Avocado Sector. Being drafted for journal submission. (Chapter 2)

Parts of this research were also presented in other symposia/conferences as listed below:

- 1) Majumdar, S., McLaren, S., Sorensen, S., & Siebert, B. (2022). Carbon and water footprinting of avocado production in New Zealand. In: *Adaptive Strategies for Future Farming*. (Eds. C.L. Christensen, D.J. Horne and R. Singh). <http://flrc.massey.ac.nz/publications.html> Occasional Report No. 34. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand.
- 2) Majumdar, S., McLaren, S., Siebert, B., & Sorensen, S. (2022). Evaluating the environmental impacts of growing avocados in New Zealand. 13th International Conference on Life Cycle Assessment of Food 2022 (LCA Foods 2022) On “The role of emerging economies in global food security” 12-14 October 2022, Lima, Peru (hybrid conference). Published as peer-reviewed extended abstract in the book of conference proceedings.

<https://bio-val.de/wp-content/uploads/2023/02/ProceedingsLCAFoods2022F.pdf>

- 3) Majumdar, S. (2022). Using Life Cycle Assessment to evaluate the environmental impact of growing avocados in New Zealand. 1st China-New Zealand Joint Symposium in Horticulture “The Science and Art of Growing Horticultural Plants”. 24-25 February 2022. Presented online.
- 4) Majumdar, S. and McLaren, S.J. (2023). Environmental Life Cycle Assessment of New Zealand Avocados. Presented at the World Avocado Congress held at Aotea Centre, Auckland, April 2023. The presentation can be accessed here: <https://industry.nzavocado.co.nz/world-avocado-congress-nz-2023/presentations/>
- 5) Majumdar, S., McLaren, S., van der Pols, J., & Lister, C. (2024). Life cycle-based environmental impacts of foods using the nutritional LCA method: a case study of New Zealand avocados and Cheddar Cheese. The 11th Australian Conference on Life Cycle Assessment. Responding to the climate emergency: metrics and tools for rational action. Mantra Twin Towns Coolangatta, Tweed Heads NSW. 19-20 July 2023. Published as peer-reviewed extended abstract in the book of conference proceedings. Received Honourable Mention in New Researcher award category. Book of proceedings available for download at: <https://www.lcaconference.com.au/2023-conference>
- 6) Majumdar, S. & McLaren, S. J. (2024). Defining benchmarks for the downstream supply chain stages for LCA-based voluntary sustainability standards: case study of the New Zealand avocado sector. 14th LCA Food International Conference. 8-12 September 2024. Barcelona, Spain. Presented as a peer-reviewed poster and included in book of conference proceedings. Book of abstracts available for download at: <https://www.lcafood2024.com/programme/book-of-abstracts>

References

- Abbott, K. W., & Snidal, D. (2008). The Governance Triangle: Regulatory Standards Institutions and The Shadow of the State. In K. W. Abbott, & D. J. Snidal (Eds.), *The Spectrum of International Institutions – An Interdisciplinary Collaboration on Global Governance* (pp. 52-91). Routledge. <https://doi-org.ezproxy.massey.ac.nz/10.4324/9781003111719>
- Abbott, M., Boyle, C., Blackburne, K., & Lee, W. (2018). New Zealand’s “arc of influence”: The “clean, blue, green” country. *Journal of Cultural Geography*, 35(3), 388–412. <https://doi.org/10.1080/08873631.2018.1435937>
- Abrams, J., Nielsen, E., Diaz, D., Selfa, T., Adams, E., Dunn, J. L., & Moseley, C. (2018). How Do States Benefit from Nonstate Governance? Evidence from Forest Sustainability Certification. *Global Environmental Politics*, 18(3), 66–85. https://doi.org/10.1162/glep_a_00470
- Akrong, R., Akorsu, A. D., Jha, P., & Agyenim, J. B. (2022). Assessing the trade and welfare effects of certification schemes: The case of GlobalGAP in Ghana’s mango sector. *Scientific African*, 18, e01425. <https://doi.org/10.1016/j.sciaf.2022.e01425>
- Aleksandrowicz, L., Green, R., Joy, E. J. M., Smith, P., & Haines, A. (2016). The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLOS ONE*, 11(11), e0165797. <https://doi.org/10.1371/journal.pone.0165797>
- Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics*, 9(3), 42. <https://doi.org/10.3390/toxics9030042>
- Amundsen, V. S., Gauteplass, A. Å., & Bailey, J. L. (2019). Level up or game over: The implications of levels of impact in certification schemes for salmon aquaculture. *Aquaculture Economics & Management*, 23(3), 237–253. <https://doi.org/10.1080/13657305.2019.1632389>
- Andersson, A., & Hammarlund, C. (2023). The effect of eco-certification on demand: The case of MSC-certified Norway lobster. *Ecological Economics*, 204, 107661. <https://doi.org/10.1016/j.ecolecon.2022.107661>
- Arton, A., Leiman, A., Petrokofsky, G., Toonen, H., & Longo, C. S. (2020). What do we know about the impacts of the Marine Stewardship Council seafood ecolabelling program? A systematic map. *Environmental Evidence*, 9(1), 6. <https://doi.org/10.1186/s13750-020-0188-9>
- ASC. (2024). *ASC farm standard—February 2024 Draft for public consultation*. <https://asc-aqua.org/wp-content/uploads/2024/04/ASC-Farm-Standard-v0.4-Draft-for-Public-Consultation-April-2024.pdf>

- Auld, G. (2010). Assessing Certification as Governance: Effects and Broader Consequences for Coffee. *The Journal of Environment & Development*, 19(2), 215–241.
<https://doi.org/10.1177/1070496510368506>
- Auld, G., & Bull, G. Q. (2003). The institutional design of forest certification standards initiatives and its influence on the role of science: The case of forest genetic resources. *Journal of Environmental Management*, 69(1), 47–62. [https://doi.org/10.1016/S0301-4797\(03\)00118-X](https://doi.org/10.1016/S0301-4797(03)00118-X)
- Auld, G., & Gulbrandsen, L. H. (2010). Transparency in Nonstate Certification: Consequences for Accountability and Legitimacy. *Global Environmental Politics* 10(3), 97–119.
https://doi.org/10.1162/GLEP_a_00016
- Auld, G., & Gulbrandsen, L. H. (2014). Learning through disclosure: The evolving importance of transparency in the practice of nonstate certification. In A. Gupta & M. Mason (Eds.), *Transparency in global environmental governance: Critical perspectives* (pp. 61–86). MIT Press.
- Auld, G., Gulbrandsen, L. H., & McDermott, C. L. (2008). Certification Schemes and the Impacts on Forests and Forestry. *Annual Review of Environment and Resources*, 33(1), 187–211.
<https://doi.org/10.1146/annurev.enviro.33.013007.103754>
- Avadí, A., & Fréon, P. (2015). A set of sustainability performance indicators for seafood: Direct human consumption products from Peruvian anchoveta fisheries and freshwater aquaculture. *Ecological Indicators*, 48, 518–532.
<https://doi.org/10.1016/j.ecolind.2014.09.006>
- Bardsley, A., Coates, B., Goldson, S., Gluckman, P., & Kaiser, M. (2020). *The future of food and the primary sector*. Available for download at: <https://informedfutures.org/the-future-of-food-the-primary-sector/>
- Basset-Mens, C., Vannière, H., Grasselly, D., Heitz, H., Braun, A., Payen, S., Koch, P., & Biard, Y. (2016). Environmental impacts of imported and locally grown fruits for the French market: A cradle-to-farm-gate LCA study. *Fruits*, 71(2), 93–104.
<https://doi.org/10.1051/fruits/2015050>
- Battle-Bayer, L., Aldaco, R., Bala, A., & Fullana-i-Palmer, P. (2020). Toward sustainable dietary patterns under a water–energy–food nexus life cycle thinking approach. *Current Opinion in Environmental Science & Health*, 13, 61–67. <https://doi.org/10.1016/j.coesh.2019.11.001>

- Beal, T. (2024). Environmentally protective diets may come with trade-offs for micronutrient adequacy. *The American Journal of Clinical Nutrition*.
<https://doi.org/10.1016/j.ajcnut.2024.01.028>
- Bell, E. M., & Horvath, A. (2020). Modeling the carbon footprint of fresh produce: Effects of transportation, localness, and seasonality on US orange markets. *Environmental Research Letters*, 15(3), 034040. <https://doi.org/10.1088/1748-9326/ab6c2f>
- Bernstein, S., & Cashore, B. (2007). Can non-state global governance be legitimate? An analytical framework. *Regulation & Governance*, 1(4), 347–371. <https://doi.org/10.1111/j.1748-5991.2007.00021.x>
- Bernstein, S., & Cashore, B. (2012). Complex global governance and domestic policies: Four pathways of influence. *International Affairs*, 88(3), 585–604.
<https://doi.org/10.1111/j.1468-2346.2012.01090.x>
- Berry, E. M., Dernini, S., Burlingame, B., Meybeck, A., & Conforti, P. (2015). Food security and sustainability: Can one exist without the other? *Public Health Nutrition*, 18(13), 2293–2302.
<https://doi.org/10.1017/S136898001500021X>
- Bessou, C., Basset-Mens, C., Latunussa, C., Vélú, A., Heitz, H., Vannière, H., & Caliman, J.-P. (2016). Partial modelling of the perennial crop cycle misleads LCA results in two contrasted case studies. *The International Journal of Life Cycle Assessment*, 21(3), 297–310.
<https://doi.org/10.1007/s11367-016-1030-z>
- Bessou, C., Basset-Mens, C., Tran, T., & Benoist, A. (2013). LCA applied to perennial cropping systems: A review focused on the farm stage. *The International Journal of Life Cycle Assessment*, 18(2), 340–361. <https://doi.org/10.1007/s11367-012-0502-z>
- BEUC. (2023). *A climate-neutral food basket-Too good to be true*
https://www.beuc.eu/sites/default/files/publications/BEUC-X-2023-025_A_climate-neutral_food_basket-Too_good_to_be_true.pdf
- Bianco, I., Thiébat, F., Carbonaro, C., Pagliolico, S., Blengini, G. A., & Comino, E. (2021). Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture. *Journal of Cleaner Production*, 324, 129249. <https://doi.org/10.1016/j.jclepro.2021.129249>
- Bissinger, K., Brandi, C., Cabrera de Leicht, S., Fiorini, M., Schleifer, P., Fernandez de Cordova, S., & Ahmed, N. (2020). *Linking Voluntary Sustainability Standards to Sustainable Development Goals*. International Trade Centre. Available for download at:
<https://unctad.org/publication/linking-voluntary-standards-sustainable-development-goals>

- Bjørn, A., Owsianiak, M., Molin, C., & Laurent, A. (2018). Main characteristics of LCA. In M.Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment, Theory and Practice* (pp. 9-16). Springer International: Switzerland. <https://doi.org/10.1007/978-3-319-56475-3>
- Blackett, P., & Le Heron, R. (2008). Maintaining the 'Clean Green' Image: Governance of On-Farm Environmental Practices in the New Zealand Dairy Industry. In Richard, L. H., & Christina, S. (Eds.) *Agri-Food Commodity Chains and Globalising Networks*, (pp. 75-87). Routledge.
- Bloom, J. D. (2015). Standards for Development: Food Safety and Sustainability in Wal-Mart's Honduran Produce Supply Chains. *Rural Sociology*, 80(2), 198–227. <https://doi.org/10.1111/ruso.12060>
- Boone, K., Broekema, R., Winter, M. van H., Verweij-Novikova, I., & Adema, H. (2023). *LCA-based labelling systems: Game changer towards more sustainable food production and consumption across Europe*. Available for download at: <https://research.wur.nl/en/publications/lca-based-labelling-systems-game-changer-towards-more-sustainable>
- Bord Bia. (2013). *Sustainable Dairy assurance scheme*. <https://www.origingreen.ie/globalassets/origin-green/og-publications/sustainable-dairy-assurance-scheme.pdf>
- Bord Bia. (2017). *Sustainable horticulture assurance scheme*. Available for download at: <https://www.bordbia.ie/farmers-growers/get-involved/become-quality-assured/sustainable-horticulture-assurance-scheme-shas/>
- Boström, M., & Hallström, K. T. (2013). Global multi-stakeholder standard setters: How fragile are they? *Journal of Global Ethics*, 9(1), 93–110. <https://doi.org/10.1080/17449626.2013.773180>
- Brown, K. A., Harris, F., Potter, C., & Knai, C. (2020). The future of environmental sustainability labelling on food products. *The Lancet Planetary Health*, 4(4), e137–e138. [https://doi.org/10.1016/S2542-5196\(20\)30074-7](https://doi.org/10.1016/S2542-5196(20)30074-7)
- Bunge, A. C., Wickramasinghe, K., Renzella, J., Clark, M., Rayner, M., Rippin, H., Halloran, A., Roberts, N., & Breda, J. (2021). Sustainable food profiling models to inform the development of food labels that account for nutrition and the environment: A systematic review. *The Lancet Planetary Health*, 5(11), e818–e826. [https://doi.org/10.1016/S2542-5196\(21\)00231-X](https://doi.org/10.1016/S2542-5196(21)00231-X)

- Burns, S. L., Yapura, P. F., & Giessen, L. (2016). State actors and international forest certification policy: Coalitions behind FSC and PEFC in federal Argentina. *Land Use Policy*, 52, 23–29. <https://doi.org/10.1016/j.landusepol.2015.12.005>
- Bush, S. R., Toonen, H., Oosterveer, P., & Mol, A. P. J. (2013). The ‘devils triangle’ of MSC certification: Balancing credibility, accessibility and continuous improvement. *Marine Policy*, 37, 288–293. <https://doi.org/10.1016/j.marpol.2012.05.011>
- Calderón, L. A., Herrero, M., Laca, A., & Díaz, M. (2018). Environmental impact of a traditional cooked dish at four different manufacturing scales: From ready meal industry and catering company to traditional restaurant and homemade. *The International Journal of Life Cycle Assessment*, 23(4), 811–823. <https://doi.org/10.1007/s11367-017-1326-7>
- Cambria, D., & Pierangeli, D. (2012). Application of a life cycle assessment to walnut tree (*Juglans regia* L.) high quality wood production: A case study in southern Italy. *Journal of Cleaner Production*, 23(1), 37–46. <https://doi.org/10.1016/j.jclepro.2011.10.031>
- Campbell, C. G., & Feldpausch, G. (2023). Teaching nutrition and sustainable food systems: Justification and an applied approach. *Frontiers in Nutrition*, 10. <https://www.frontiersin.org/articles/10.3389/fnut.2023.1167180>
- Cao, L., Diana, J. S., & Keoleian, G. A. (2013). Role of life cycle assessment in sustainable aquaculture. *Reviews in Aquaculture*, 5(2), 61–71. <https://doi.org/10.1111/j.1753-5131.2012.01080.x>
- Cashore, B. (2002). Legitimacy and the Privatization of Environmental Governance: How Non–State Market–Driven (NSMD) Governance Systems Gain Rule–Making Authority. *Governance*, 15(4), 503–529. <https://doi.org/10.1111/1468-0491.00199>
- Cashore, B., Elliott, C., Pohnan, E., Stone, M., & Jodoin, S. (2015). Achieving sustainability through market mechanisms. In *Business and Sustainability*.
- Cashore, B. W., Auld, G., & Newsom, D. (2004). *Governing Through Markets: Forest Certification and the Emergence of Non-state Authority*. Yale University Press.
- Castellani, V., Sala, S., & Benini, L. (2017). Hotspots analysis and critical interpretation of food life cycle assessment studies for selecting eco-innovation options and for policy support. *Journal of Cleaner Production*, 140, 556–568. <https://doi.org/10.1016/j.jclepro.2016.05.078>
- Cerutti, A. K., Beccaro, G. L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., & Bounous, G. (2014). Life cycle assessment application in the fruit sector: State of the art and recommendations

- for environmental declarations of fruit products. *Journal of Cleaner Production*, 73, 125–135.
<https://doi.org/10.1016/j.jclepro.2013.09.017>
- Changing Markets Foundation. (2023). *Feeding Us Greenwash An analysis of misleading claims in the food sector*. Available for download at: <https://changingmarkets.org/report/feeding-us-greenwash-an-analysis-of-misleading-claims-in-the-food-sector/>
- Chin, T. A., Tat, H. H., & Sulaiman, Z. (2015). Green Supply Chain Management, Environmental Collaboration and Sustainability Performance. *Procedia CIRP*, 26, 695–699.
<https://doi.org/10.1016/j.procir.2014.07.035>
- Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences*, 116(46), 23357–23362.
<https://doi.org/10.1073/pnas.1906908116>
- Clark, M., Hill, J., & Tilman, D. (2018). The Diet, Health, and Environment Trilemma. *Annual Review of Environment and Resources*, 43(1), 109–134. <https://doi.org/10.1146/annurev-environ-102017-025957>
- Clark, M., Springmann, M., Rayner, M., Scarborough, P., Hill, J., Tilman, D., Macdiarmid, J. I., Fanzo, J., Bandy, L., & Harrington, R. A. (2022). Estimating the environmental impacts of 57,000 food products. *Proceedings of the National Academy of Sciences*, 119(33), e2120584119.
<https://doi.org/10.1073/pnas.2120584119>
- Cossu, D., Zanchi, L., Maranghi, S., Zamagni, A., Gaias, G., Duce, P., & Vagnoni, E. (2023). Ecolabelling for improving sustainability of agri-food supply chain: An experimental implementation of the made green in Italy scheme on the hard sheep milk cheese. *Cleaner Environmental Systems*, 100153. <https://doi.org/10.1016/j.cesys.2023.100153>
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), Article 3. <https://doi.org/10.1038/s43016-021-00225-9>
- Cucurachi, S., Seager, T. P., & Prado, V. (2017). Normalization in Comparative Life Cycle Assessment to Support Environmental Decision Making. *Journal of Industrial Ecology*, 21(2), 242–243. <https://doi.org/10.1111/jiec.12549>
- Czarnezki, Jason J. (2011). The Future of Food Eco-Labeling: Organic, Carbon Footprint, and Environmental Life-Cycle Analysis. Vermont Law School Research Paper No. 10-44, *Stanford Environmental Law Journal*, Vol. 30(3). Available for download at: <https://ssrn.com/abstract=1645860>

- De Bauw, M., Vranken, L., & Matthys, C. (2022). Bridging gaps in food labelling. *Nutrition Bulletin*, 47(1), 2–8. <https://doi.org/10.1111/nbu.12539>
- DeFries, R. S., Fanzo, J., Mondal, P., Remans, R., & Wood, S. A. (2017). Is voluntary certification of tropical agricultural commodities achieving sustainability goals for small-scale producers? A review of the evidence. *Environmental Research Letters*, 12(3), 033001. <https://doi.org/10.1088/1748-9326/aa625e>
- Dias, G. M., Ayer, N. W., Khosla, S., Van Acker, R., Young, S. B., Whitney, S., & Hendricks, P. (2017). Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. *Journal of Cleaner Production*, 140, 831–839. <https://doi.org/10.1016/j.jclepro.2016.06.039>
- Dietz, T., Grabs, J., & Chong, A. E. (2021). Mainstreamed voluntary sustainability standards and their effectiveness: Evidence from the Honduran coffee sector. *Regulation & Governance*, 15(2), 333–355. <https://doi.org/10.1111/regg.12239>
- Dijkman, T. J., Basset-Mens, C., Antón, A., & Núñez, M. (2018). LCA of Food and Agriculture. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 723–754). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_29
- Directorate-General for Research and Innovation (European Commission), & Group of Chief Scientific Advisors (European Commission). (2020). *Towards a Sustainable Food System: Moving from food as a commodity to food as more of a common good : independent expert report*. Publications Office of the European Union. Available for download at: <https://data.europa.eu/doi/10.2777/282386>
- Dodds, R., Graci, S., Ko, S., & Walker, L. (2013). What drives environmental sustainability in the New Zealand wine industry?: An examination of driving factors and practices. *International Journal of Wine Business Research*, 25(3), 164–184. <https://doi.org/10.1108/IJWBR-2012-0015>
- Dudley, N., & Alexander, S. (2017). Agriculture and biodiversity: A review. *Biodiversity*, 18(2–3), 45–49. <https://doi.org/10.1080/14888386.2017.1351892>
- Dulvy, N. K., Pacoureau, N., Rigby, C. L., Pollom, R. A., Jabado, R. W., Ebert, D. A., Finucci, B., Pollock, C. M., Cheek, J., Derrick, D. H., Herman, K. B., Sherman, C. S., VanderWright, W. J., Lawson, J. M., Walls, R. H. L., Carlson, J. K., Charvet, P., Bineesh, K. K., Fernando, D., ... Simpfendorfer, C. A. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, 31(21), 4773–4787.e8. <https://doi.org/10.1016/j.cub.2021.08.062>

- Eddy, T. D., Lam, V. W. Y., Reygondeau, G., Cisneros-Montemayor, A. M., Greer, K., Palomares, M. L. D., Bruno, J. F., Ota, Y., & Cheung, W. W. L. (2021). Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*, 4(9), 1278–1285.
<https://doi.org/10.1016/j.oneear.2021.08.016>
- Eme, P. E., Douwes, J., Kim, N., Foliaki, S., & Burlingame, B. (2019). Review of Methodologies for Assessing Sustainable Diets and Potential for Development of Harmonised Indicators. *International Journal of Environmental Research and Public Health*, 16(7), 1184.
<https://doi.org/10.3390/ijerph16071184>
- Ernstoff, A., Stylianou, K. S., Sahakian, M., Godin, L., Dauriat, A., Humbert, S., Erkman, S., & Jolliet, O. (2020). Towards Win-Win Policies for Healthy and Sustainable Diets in Switzerland. *Nutrients*, 12(9), 2745. <https://doi.org/10.3390/nu12092745>
- Esteve-Llorens, X., Ita-Nagy, D., Parodi, E., González-García, S., Moreira, M. T., Feijoo, G., & Vázquez-Rowe, I. (2022). Environmental footprint of critical agro-export products in the Peruvian hyper-arid coast: A case study for green asparagus and avocado. *Science of The Total Environment*, 818, 151686. <https://doi.org/10.1016/j.scitotenv.2021.151686>
- EU Commission. (2019). *EU Green Public Procurement Criteria and Requirements*. https://green-business.ec.europa.eu/green-public-procurement/gpp-criteria-and-requirements_en (Accessed 21 August 2024).
- European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD) Handbook: General guide for life cycle assessment-detailed guidance*. Publications Office. Available for download at: <https://data.europa.eu/doi/10.2788/38479>
- European Commission, Umweltbundesamt, Pré, 2.0 LCA., RISE., & Heid und Partner Rechtsanwälte GmbH. (2021). *Study on the implementation of life cycle assessment and environmental footprint methods in the context of public procurement: Final report*. Publications Office. Available for download at: <https://data.europa.eu/doi/10.2779/74025>
- European Parliament. (2023). *EU to ban greenwashing and improve consumer information on product durability*. <https://www.europarl.europa.eu/news/en/press-room/20230918IPR05412/eu-to-ban-greenwashing-and-improve-consumer-information-on-product-durability> (Accessed 21 September 2024)
- European Union. (2020). *Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System*. https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf

- FAO. (2014). *SAFA guidelines: Sustainability assessment of food and agriculture systems* (Version 3.0). Available for download at: <https://openknowledge.fao.org/items/84c84661-7172-415c-b66e-7c1eee5db675>
- Nguyen, H. (2018). *Sustainable food systems: Concept and framework*. Available for download at: <https://openknowledge.fao.org/items/8d2575e3-e701-4b1d-8e20-d9c83179c848>
- FAO (2019). *The State of Food and Agriculture – Moving forward on food loss and waste reduction*. Available for download at: <https://www.fao.org/interactive/state-of-food-agriculture/2019/en/>
- FAO. (2020). *Vietnam – National Action Plan on Sustainable Consumption and Production (2021-2030)*. <https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC213439/> (Accessed 25 July 2024)
- FAO. (2021a). *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point*. Available for download at: <https://doi.org/10.4060/cb7654en>
- FAO. (2023). *Tracking progress on food and agriculture-related SDG indicators 2023*. Available for download at: <https://doi.org/10.4060/cc7088en>
- FAO. (2021). *Life Cycle Assessment for sustainable food systems*. Agrifood-Systems. <https://www.fao.org/food-systems/news/news-detail/Life-Cycle-Assessment-for-sustainable-food-systems/en> (Accessed 12 September 2024)
- FAO & Alliance of Biodiversity International and CIAT (2021). *Public food procurement for sustainable food systems and healthy diets—Volume 2*. <https://doi.org/10.4060/cb7969en>
- FAO, IFAD, UNICEF, & WFP. (2022). *The State of Food Security and Nutrition in the World 2022*. <https://doi.org/10.4060/cc0639en>
- FAO and WHO (2019). *Sustainable healthy diets - guiding principles*. Available for download at: <https://www.who.int/publications/i/item/9789241516648>
- Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of The Total Environment*, 805, 150106. <https://doi.org/10.1016/j.scitotenv.2021.150106>
- Fiorini, M., Hoekman, B. M., Jansen, M., Schleifer, P., Solleder, O., Taimasova, R., & Wozniak, J. (2019). Institutional design of voluntary sustainability standards systems: Evidence from a new database. *Development Policy Review*, 37(2), 0193-0212. <https://cadmus.eui.eu/handle/1814/66037>

- Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., ... Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, 478(7369), Article 7369.
<https://doi.org/10.1038/nature10452>
- Foley, P. (2017). The territorialization of transnational sustainability governance: Production, power and globalization in Iceland's fisheries. *Environmental Politics*, 26(5), 915–937.
<https://doi.org/10.1080/09644016.2017.1343767>
- Foote, K. J., Joy, M. K., & Death, R. G. (2015). New Zealand Dairy Farming: Milking Our Environment for All Its Worth. *Environmental Management*, 56(3), 709–720.
<https://doi.org/10.1007/s00267-015-0517-x>
- Nicese, F. P., & Lazzerini, G. (2012). *CO₂ sources and sinks in ornamental plant nurseries*, International Society for Horticultural Science. ISHS Acta Horticulturae 990: II International Symposium on Woody Ornamentals of the Temperate Zone
http://www.actahort.org/books/990/990_8.htm
- Frankowska, A., Jeswani, H. K., & Azapagic, A. (2019). Life cycle environmental impacts of fruits consumption in the UK. *Journal of Environmental Management*, 248, 109111.
<https://doi.org/10.1016/j.jenvman.2019.06.012>
- Freidberg, S. (2017). Big Food and Little Data: The Slow Harvest of Corporate Food Supply Chain Sustainability Initiatives. *Annals of the American Association of Geographers*, 107(6), 1389–1406. <https://doi.org/10.1080/24694452.2017.1309967>
- FSANZ. (2023). *Nutrition information panels*.
<https://www.foodstandards.gov.au/consumer/labelling/panels> (Accessed 1 October 2024)
- Fuchs, D., Kalfagianni, A., & Havinga, T. (2011). Actors in private food governance: The legitimacy of retail standards and multistakeholder initiatives with civil society participation. *Agriculture and Human Values*, 28(3), 353–367.
<https://doi.org/10.1007/s10460-009-9236-3>
- Gale, F., & Haward, M. (2011). Comparative Analysis of State Responses to the FSC and the MSC. In F. Gale & M. Haward (Eds.), *Global Commodity Governance: State Responses to Sustainable Forest and Fisheries Certification* (pp. 233–258). Palgrave Macmillan UK.
https://doi.org/10.1057/9780230304697_8

- Galindro, B. M., Zanghelini, G. M., & Soares, S. R. (2019). Use of benchmarking techniques to improve communication in life cycle assessment: A general review. *Journal of Cleaner Production*, 213, 143–157. <https://doi.org/10.1016/j.jclepro.2018.12.147>
- Gasper, D., Shah, A., & Tankha, S. (2019). The Framing of Sustainable Consumption and Production in SDG 12. *Global Policy*, 10(S1), 83–95. <https://doi.org/10.1111/1758-5899.12592>
- Gasso, V., Barber, A., Moller, H., Bayonne, E., Oudshoorn, F. W., & Sørensen, C. G. (2025). Benchmarking for locally tuned sustainability: The case of energy and water use in New Zealand vineyards. *Environmental and Sustainability Indicators*, 25, 100536. <https://doi.org/10.1016/j.indic.2024.100536>
- Ghadimi, P., Wang, C., Azadnia, A. H., Lim, M. K., & Sutherland, J. W. (2019). Life cycle-based environmental performance indicator for the coal-to-energy supply chain: A Chinese case application. *Resources, Conservation and Recycling*, 147, 28–38. <https://doi.org/10.1016/j.resconrec.2019.04.021>
- Giessen, L., Burns, S., Sahide, M. A. K., & Wibowo, A. (2016). From governance to government: The strengthened role of state bureaucracies in forest and agricultural certification. *Policy and Society*, 35(1), 71–89. <https://doi.org/10.1016/j.polsoc.2016.02.001>
- Global Nutrition Report. (2021). *2021 Global Nutrition Report: The state of global nutrition*. Available for download at: <https://globalnutritionreport.org/reports/2021-global-nutrition-report/>
- Global Panel on Agriculture and Food Systems for Nutrition. (2020). *Foresight 2.0. Future food systems: For people, planet, and prosperity*. Global Panel for Agriculture and Food Systems for Nutrition. <https://foresight.glopan.org/>
- Gómez-Ramos, A., & Rico Gonzalez, M. (2023). The contribution of green public food procurement to sustainability: Evidence from two case studies in Spain. *Agroecology and Sustainable Food Systems*, 47(8), 1158–1185. <https://doi.org/10.1080/21683565.2023.2223555>
- Gow, J., Rana, R. H., Moscovici, D., Ugaglia, A. A., Valenzuela, L., Mihailescu, R., & Coelli, R. (2022). Australian consumers and environmental characteristics of wine: Price premium indications. *International Journal of Wine Business Research*, 34(4), 542–566. <https://doi.org/10.1108/IJWBR-04-2021-0024>
- Graham, F., Russell, J., Holdsworth, M., Menon, M., & Barker, M. (2019). Exploring the Relationship between Environmental Impact and Nutrient Content of Sandwiches and

- Beverages Available in Cafés in a UK University. *Sustainability*, 11(11), Article 11.
<https://doi.org/10.3390/su11113190>
- Green Growth Advisory Group. (2011). *Greening New Zealand's Growth*.
https://img.scoop.co.nz/media/pdfs/1203/Greening_New_Zealands_Growth.pdf
- Grigoriadis, V., Nugent, A., & Brereton, P. (2021). Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends in Food Science & Technology*, 112, 298–311. <https://doi.org/10.1016/j.tifs.2021.03.047>
- Grosso, G., Mateo, A., Rangelov, N., Buzeti, T., Birt, C., & on behalf of the Food and Nutrition Section of the European Public Health Association. (2020). Nutrition in the context of the Sustainable Development Goals. *European Journal of Public Health*, 30(Supplement_1), i19–i23. <https://doi.org/10.1093/eurpub/ckaa034>
- Gruère, G. (2013). *A Characterisation of Environmental Labelling and Information Schemes—OECD environment working papers no. 62* (OECD Environment Working Papers 62; OECD Environment Working Papers, Vol. 62). <https://doi.org/10.1787/5k3z11hpdgq2-en>
- Gu, D., Andreev, K., & Dupre, M. E. (2021). Major Trends in Population Growth Around the World. *China CDC Weekly*, 3(28), 604–613. <https://doi.org/10.46234/ccdcw2021.160>
- Gulbrandsen, L. H. (2008). *Non-state global environmental governance: The emergence and effectiveness of forest and fisheries certification schemes* [Doctoral dissertation, University of Oslo, Norway]. <https://core.ac.uk/download/pdf/30835322.pdf>
- Haack, P., & Rasche, A. (2021). The Legitimacy of Sustainability Standards: A Paradox Perspective. *Organization Theory*, 2(4), 26317877211049493.
<https://doi.org/10.1177/26317877211049493>
- Hallström, E., Carlsson-Kanyama, A., & Börjesson, P. (2015). Environmental impact of dietary change: A systematic review. *Journal of Cleaner Production*, 91, 1–11.
<https://doi.org/10.1016/j.jclepro.2014.12.008>
- Hatanaka, M., & Konefal, J. (2013). Legitimacy and Standard Development in Multi-stakeholder Initiatives: A Case Study of the Leonardo Academy's Sustainable Agriculture Standard Initiative. *The International Journal of Sociology of Agriculture and Food*, 20(2), 155–173.
<https://doi.org/10.48416/ij saf.v20i2.191>
- Hatanaka, M., Konefal, J., Strube, J., Glenna, L., & Conner, D. (2022). Data-Driven Sustainability: Metrics, Digital Technologies, and Governance in Food and Agriculture*. *Rural Sociology*, 87(1), 206–230. <https://doi.org/10.1111/ruso.12415>

- Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-56475-3>
- Heinonen, J., Säynäjoki, A., Junnonen, J. M., Pöyry, A., & Junnila, S. (2016). Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator? *Building and Environment*, 95, 116–125. <https://doi.org/10.1016/j.buildenv.2015.09.006>
- Hélias, A., van der Werf, H. M. G., Soler, L.-G., Aggeri, F., Dourmad, J.-Y., Julia, C., Nabec, L., Pellerin, S., Ruffieux, B., & Trystram, G. (2022). Implementing environmental labelling of food products in France. *The International Journal of Life Cycle Assessment*, 27(7), 926–931. <https://doi.org/10.1007/s11367-022-02071-8>
- Heller, M. C., Keoleian, G. A., & Willett, W. C. (2013). Toward a Life Cycle-Based, Diet-level Framework for Food Environmental Impact and Nutritional Quality Assessment: A Critical Review. *Environmental Science & Technology*, 47(22), 12632–12647. <https://doi.org/10.1021/es4025113>
- Henriksson, P. J.G., Cucurachi, S., Guinée, J. B., Heijungs, R., Troell, M., & Ziegler, F. (2021). A rapid review of meta-analyses and systematic reviews of environmental footprints of food commodities and diets. *Global Food Security*, 28, 100508. <https://doi.org/10.1016/j.gfs.2021.100508>
- Hieke, S., & Harris, J. L. (2016). Nutrition information and front-of-pack labelling: Issues in effectiveness. *Public Health Nutrition*, 19(12), 2103–2105. <https://doi.org/10.1017/S1368980016001890>
- HLPE. (2020). *Food security and nutrition: Building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*. <https://www.fao.org/3/ca9731en/ca9731en.pdf>
- Hodgkins, C. E., Raats, M. M., Fife-Schaw, C., Peacock, M., Gröppel-Klein, A., Koenigstorfer, J., Wasowicz, G., Stysko-Kunkowska, M., Gulcan, Y., Kustepeli, Y., Gibbs, M., Shepherd, R., & Grunert, K. G. (2015). Guiding healthier food choice: Systematic comparison of four front-of-pack labelling systems and their effect on judgements of product healthiness. *British Journal of Nutrition*, 113(10), 1652–1663. <https://doi.org/10.1017/S0007114515000264>
- Holenweger, G., Stöckli, S., & Brügger, A. (2023). Carbon footprint labels involving traffic lights foster sustainable food choices. *Food Quality and Preference*, 106, 104813. <https://doi.org/10.1016/j.foodqual.2023.104813>

- Horne, R. E. (2009). Limits to labels: The role of eco-labels in the assessment of product sustainability and routes to sustainable consumption. *International Journal of Consumer Studies*, 33(2), 175–182. <https://doi.org/10.1111/j.1470-6431.2009.00752.x>
- Hossain, A., Krupnik, T. J., Timsina, J., Mahboob, M. G., Chaki, A. K., Farooq, M., Bhatt, R., Fahad, S., & Hasanuzzaman, M. (2020). Agricultural Land Degradation: Processes and Problems Undermining Future Food Security. In S. Fahad, M. Hasanuzzaman, M. Alam, H. Ullah, M. Saeed, I. Ali Khan, & M. Adnan (Eds.), *Environment, Climate, Plant and Vegetation Growth* (pp. 17–61). Springer International Publishing. https://doi.org/10.1007/978-3-030-49732-3_2
- ISO (2006). *ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework*. Geneva, Switzerland: ISO.
- ISO. (2019). *Environmental labels*. <https://www.iso.org/publication/PUB100323.html> (Accessed 18 September 2024)
- ISO. (2022). *ISO 14020:2022. Environmental statements and programmes for products— Principles and general requirements*. ISO. <https://www.iso.org/standard/79479.html> (Accessed 18 September 2024)
- ITC (2023). *StandardsMap - The world's largest database for sustainability standards*. <https://www.standardsmap.org/en/home> (Accessed 19 September 2024)
- Jacob-John, J., D'Souza, C., Marjoribanks, T., & Singaraju, S. (2021). Synergistic Interactions of SDGs in Food Supply Chains: A Review of Responsible Consumption and Production. *Sustainability*, 13(16), Article 16. <https://doi.org/10.3390/su13168809>
- Jolliet, O. (2022). Integrating Dietary Impacts in Food Life Cycle Assessment. *Frontiers in Nutrition*, 9, 898180. <https://doi.org/10.3389/fnut.2022.898180>
- Kaefer, F. (2014). *Credibility at Stake? News representations and Discursive Constructions of National Environmental Reputation and Place Brand*. Available to download at: <https://researchcommons.waikato.ac.nz/entities/publication/aad75154-0f28-4db2-a6ba-e7ff80deeb12>
- Keyes, S., Tyedmers, P., & Beazley, K. (2015). Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. *Journal of Cleaner Production*, 104, 40–51. <https://doi.org/10.1016/j.jclepro.2015.05.037>
- Kietzmann, A. (2024). *Eco-labels*. Institut Bauen Und Umwelt e.V. <https://ibu-epd.com/umweltzeichen/> (Accessed 20 November 2024)

- Klöpffer, W., & Grahl, B. (2013). *Life cycle assessment (LCA): A guide to best practice*. Wiley-VCH: Germany.
- Koerber, K. von, Bader, N., & Leitzmann, C. (2017). Wholesome Nutrition: An example for a sustainable diet. *Proceedings of the Nutrition Society*, 76(1), 34–41.
<https://doi.org/10.1017/S0029665116000616>
- Konefal, J., Hatanaka, M., Strube, J., Glenna, L., & Conner, D. (2022). Sustainability assemblages: From metrics development to metrics implementation in United States agriculture. *Journal of Rural Studies*, 92, 502–509. <https://doi.org/10.1016/j.jrurstud.2019.10.023>
- Kühne, S. J., Reijnen, E., Laasner Vogt, L., & Baumgartner, M. (2023). Can carbon labels encourage green food choices? *Frontiers in Psychology*, 13.
<https://www.frontiersin.org/articles/10.3389/fpsyg.2022.902869>
- Lam, W. Y., Sim, S., Kulak, M., Van Zelm, R., Schipper, A. M., & Huijbregts, M. A. J. (2021). Drivers of variability in greenhouse gas footprints of crop production. *Journal of Cleaner Production*, 315, 128121. <https://doi.org/10.1016/j.jclepro.2021.128121>
- Lambin, E. F., & Thorlakson, T. (2018). Sustainability Standards: Interactions Between Private Actors, Civil Society, and Governments. *Annual Review of Environment and Resources*, 43(1), 369–393. <https://doi.org/10.1146/annurev-environ-102017-025931>
- Lazzerini, G., Lucchetti, S., & Nicese, F. P. (2014). Analysis of greenhouse gas emissions from ornamental plant production: A nursery level approach. *Urban Forestry & Urban Greening*, 13(3), 517–525. <https://doi.org/10.1016/j.ufug.2014.02.004>
- Lees, D. N. (2020). *The Irish Origin Green Sustainability Brand An Evaluation of the Relevance for New Zealand*. Available for download at:
<https://researcharchive.lincoln.ac.nz/entities/publication/5aa2f4e9-fe59-4b76-b016-ad536d200a2d>
- Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., & Raubenheimer, D. (2022). Global food-miles account for nearly 20% of total food-systems emissions. *Nature Food*, 3(6), Article 6.
<https://doi.org/10.1038/s43016-022-00531-w>
- Life Cycle Initiative. (2012). *What is Life Cycle Thinking? - Life Cycle Initiative*.
<https://www.lifecycleinitiative.org/activities/what-is-life-cycle-thinking/> (Accessed 10 November 2024)

- Lo, A. Y., & Cong, R. (2022). Emission reduction targets and outcomes of the Clean Development Mechanism (2005–2020). *PLOS Climate*, 1(8), e0000046.
<https://doi.org/10.1371/journal.pclm.0000046>
- Lockie, S., Traverro, J., & Tennent, R. (2015). Private food standards, regulatory gaps and plantation agriculture: Social and environmental (ir)responsibility in the Philippine export banana industry. *Journal of Cleaner Production*, 107, 122–129.
<https://doi.org/10.1016/j.jclepro.2014.03.039>
- Loconto, A., & Dankers, C. (2014). *Impact of international voluntary standards on smallholder market participation in developing countries*. Available for download at:
<https://openknowledge.fao.org/items/308a8c7a-ad7f-4211-83d2-84c97618e0af>
- Mackay, S., Gerritsen, S., Sing, F., Vandevijvere, S., & Swinburn, B. (2022). Implementing healthy food environment policies in New Zealand: Nine years of inaction. *Health Research Policy and Systems*, 20(1), 8. <https://doi.org/10.1186/s12961-021-00809-8>
- Marrucci, L., Corcelli, F., Daddi, T., & Iraldo, F. (2022). Using a life cycle assessment to identify the risk of “circular washing” in the leather industry. *Resources, Conservation and Recycling*, 185, 106466. <https://doi.org/10.1016/j.resconrec.2022.106466>
- Marx, A. (2013). Varieties of legitimacy: A configurational institutional design analysis of eco-labels. *Innovation: The European Journal of Social Science Research*, 26(3), 268–287.
<https://doi.org/10.1080/13511610.2013.771892>
- Marx, A., Depoorter, C., & Vanhaecht, R. (2022). Voluntary Sustainability Standards: State of the Art and Future Research. *Standards*, 2(1), Article 1.
<https://doi.org/10.3390/standards2010002>
- Masood, A. (2015). *GlobalGAP Certification and International Trade Flows* [Doctoral dissertation, Georg-August-University, Göttingen]. Göttingen State and University Library ediss, <https://doi.org/10.53846/goediss-4895>
- Mazac, R., Järviö, N., & Tuomisto, H. L. (2023). Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. *Science of The Total Environment*, 876, 162796. <https://doi.org/10.1016/j.scitotenv.2023.162796>
- McAloone, T. C., & Pigosso, D. C. A. (2018). Ecodesign Implementation and LCA. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 545–576). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_23

- McAuliffe, G. A., Takahashi, T., & Lee, M. R. F. (2018). Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. *Food and Energy Security*, 7(3), e00143. <https://doi.org/10.1002/fes3.143>
- McGarr-O'Brien, K., Herron, J., Shalloo, L., De Boer, I. J. M., & De Olde, E. M. (2023). Characterising sustainability certification standards in dairy production. *Animal*, 17(7), 100863. <https://doi.org/10.1016/j.animal.2023.100863>
- McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., De Camillis, C., Renouf, M., Rugani, B., Saarinen, M., van der Pols, J., Vázquez-Rowe, I., Vallejo, A. A., Bianchi, M., Chaudhary, A., Chen, C., Cooreman-Algoed, M., Dong, H., Grant, T., ... van Zanten, H. (2021a). *Integration of environment and nutrition in life cycle assessment of food Items: Opportunities and challenges*. <https://doi.org/10.4060/cb8054en>
- McLaren, S., Clothier, B., Barber, A., McNally, S., Bullen, L., Mazzetto, A., & Ledgard, S. (2021). *Updating the carbon footprints for selected New Zealand agricultural products*. <https://www.mpi.govt.nz/dmsdocument/51079-Updating-the-carbon-footprint-for-selected-New-Zealand-agricultural-products-an-update-for-apples-kiwifruit-and-wine/>
- Meemken, E.M. (2020). Do smallholder farmers benefit from sustainability standards? A systematic review and meta-analysis. *Global Food Security*, 26, 100373. <https://doi.org/10.1016/j.gfs.2020.100373>
- Meier, T., & Christen, O. (2013). Environmental Impacts of Dietary Recommendations and Dietary Styles: Germany As an Example. *Environmental Science & Technology*, 47(2), 877–888. <https://doi.org/10.1021/es302152v>
- Mekonnen, M. M., & Hoekstra, A. Y. (2014). Water footprint benchmarks for crop production: A first global assessment. *Ecological Indicators*, 46, 214–223. <https://doi.org/10.1016/j.ecolind.2014.06.013>
- Melse-Boonstra, A. (2020). Bioavailability of Micronutrients From Nutrient-Dense Whole Foods: Zooming in on Dairy, Vegetables, and Fruits. *Frontiers in Nutrition*, 7, 101. <https://doi.org/10.3389/fnut.2020.00101>
- Merli, R., Preziosi, M., & Acampora, A. (2018). Sustainability experiences in the wine sector: Toward the development of an international indicators system. *Journal of Cleaner Production*, 172, 3791–3805. <https://doi.org/10.1016/j.jclepro.2017.06.129>
- MfE. (2023). *Agriculture emissions and climate change*. Ministry for the Environment. <https://environment.govt.nz/facts-and-science/climate-change/agriculture-emissions-climate-change/> (Accessed 15 November 2024)

- MfE. (2024a). *New Zealand's Greenhouse Gas Inventory 1990–2022: Snapshot*. Ministry for the Environment. <https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-19902023-snapshot/> (Accessed 15 November 2024)
- MfE. (2024b). *Greenhouse gas emissions targets and reporting*. Ministry for the Environment. <https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/greenhouse-gas-emissions-targets-and-reporting/> (Accessed 24 December 2024)
- Minister of Climate & MfE. (2022). *Towards a productive, sustainable and inclusive economy: Aotearoa New Zealand's first emissions reduction plan*. Available for download at: <https://environment.govt.nz/publications/aotearoa-new-zealands-first-emissions-reduction-plan/>
- Mohan, R. (2018). *Use of life cycle assessment (LCA) to facilitate continuous improvement of on-farm environmental performance: A sheep dairy case study* [Master's thesis, Massey University]. Massey research online. <https://mro.massey.ac.nz/handle/10179/14849>
- Montero-Navarro, A., González-Torres, T., Rodríguez-Sánchez, J.-L., & Gallego-Losada, R. (2021). A bibliometric analysis of greenwashing research: A closer look at agriculture, food industry and food retail. *British Food Journal*, 123(13), 547–560. <https://doi.org/10.1108/BFJ-06-2021-0708>
- Mori Junior, R., Franks, D. M., & Ali, S. H. (2015). *Designing sustainability certification for greater impact: An analysis of the design characteristics of 15 sustainability certification schemes in the mining industry*. Centre for Social Responsibility in Mining, University of Queensland. <https://core.ac.uk/reader/43375360>
- Mori Junior, R., Franks, D. M., & Ali, S. H. (2016). Sustainability certification schemes: Evaluating their effectiveness and adaptability. *Corporate Governance*, 16(3), 579–592. <https://doi.org/10.1108/CG-03-2016-0066>
- Mosquini, L. H. N., Delinchant, B., & Jusselme, T. (2024). Dynamic LCA methodology to support post-occupancy decision-making for carbon budget compliance. *Energy and Buildings*, 309, 114006. <https://doi.org/10.1016/j.enbuild.2024.114006>
- MPI. (2023). *The future of Aotearoa New Zealand's food sector: Exploring demand opportunities in the year 2050*. <https://www.mpi.govt.nz/dmsdocument/56350-The-Future-of-Aotearoa-New-Zealands-Food-Sector-Exploring-Global-Demand-Opportunities-in-the-Year-2050/>

- Muigua, K. (2023). *Greenwashing: A hindrance to Achieving Sustainability?* Available for download at: <https://kmco.co.ke/articles-publications/greenwashing-a-hindrance-to-achieving-sustainability-kariuki-muigua-august-223/>
- Mungkung, R., Udo De Haes, H., & Clift, R. (2006). Potentials and Limitations of Life Cycle Assessment in Setting Ecolabelling Criteria: A Case Study of Thai Shrimp Aquaculture Product (5 pp). *The International Journal of Life Cycle Assessment*, 11(1), 55–59. <https://doi.org/10.1065/lca2006.01.238>
- Neamtu, B., & Dragos, D. C. (2015). Sustainable Public Procurement: The Use of Eco-Labels. *European Procurement & Public Private Partnership Law Review*, 10(2), 92–101. <https://www.jstor.org/stable/26639578>
- Negi, A., Pérez-Pineda, J. A., & Blankenbach, J. (Eds.). (2020). *Sustainability Standards and Global Governance: Experiences of Emerging Economies*. Springer Singapore. <https://doi.org/10.1007/978-981-15-3473-7>
- Nicholls, J., & Drewnowski, A. (2021). Toward Sociocultural Indicators of Sustainable Healthy Diets. *Sustainability*, 13(13), Article 13. <https://doi.org/10.3390/su13137226>
- Nilsson-Lindén, H., Diedrich, A., & Baumann, H. (2021). Life Cycle Work: A Process Study of the Emergence and Performance of Life Cycle Practice. *Organization & Environment*, 34(1), 99–122. <https://doi.org/10.1177/1086026619893971>
- Notarnicola, B., Sala, S., Anton, A., McLaren, S. J., Saouter, E., & Sonesson, U. (2017). The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, 140, 399–409. <https://doi.org/10.1016/j.jclepro.2016.06.071>
- Notarnicola, B., Salomone, R., Petti, L., Renzulli, P. A., Roma, R., & Cerutti, A. K. (Eds.). (2015). *Life Cycle Assessment in the Agri-food Sector: Case Studies, Methodological Issues and Best Practices*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-11940-3>
- Nyberg, O., Rico, A., Guinée, J. B., & Henriksson, P. J. G. (2021). Characterizing antibiotics in LCA—a review of current practices and proposed novel approaches for including resistance. *The International Journal of Life Cycle Assessment*, 26(9), 1816–1831. <https://doi.org/10.1007/s11367-021-01908-y>
- OECD. (1975). *The Polluter Pays Principle: Definition, Analysis, Implementation*. OECD. <https://doi.org/10.1787/9789264044845-en>

- One Planet Network. (2017). *SCP UNEP briefing*
<https://www.oneplanetnetwork.org/knowledge-centre/resources/make-case-scp-toolkit-10yfp-national-focal-points> (Accessed 16 December 2024)
- One Planet Network. (2021). *The 10-Year Framework of Programmes on Sustainable Consumption and Production*. <https://www.oneplanetnetwork.org/about/10-year-framework-programmes-sustainable-consumption-production> (Accessed 16 December 2024)
- One Planet Network. (2022). *10YFP Programmes for Sustainable Consumption and Production*. <https://www.oneplanetnetwork.org/home> (Accessed 16 December 2024)
- One Planet Network. (2024). *SCP Policies—Target 12.1*.
<https://www.oneplanetnetwork.org/sdg-12-hub/see-progress-on-sdg-12-by-target/121-policy> (Accessed 16 December 2024)
- Oosterveer, P., Adjei, B. E., Vellema, S., & Slingerland, M. (2014). Global sustainability standards and food security: Exploring unintended effects of voluntary certification in palm oil. *Global Food Security*, 3(3), 220–226. <https://doi.org/10.1016/j.gfs.2014.09.006>
- Osei-Owusu, A. K., Towa, E., & Thomsen, M. (2022). Exploring the pathways towards the mitigation of the environmental impacts of food consumption. *Science of The Total Environment*, 806, 150528. <https://doi.org/10.1016/j.scitotenv.2021.150528>
- Palliser, C. C., Rutherford, J. C., & MacCormick, A. (2019). Eutrophication in Lake Rotorua. 1. Using OVERSEER to estimate historic nitrogen loads. *New Zealand Journal of Agricultural Research*, 62(1), 112–129. <https://doi.org/10.1080/00288233.2018.1488748>
- Panainte, M., Inglezakis, V., Caraman, I., Nicolescu, M. C., Mosnegu, E., & Nedeff, F. (2014). The evolution of eco-labeled products in romania. *Environmental Engineering and Management Journal*, 13(7), Article 7.
- Paratscha, R., Von Der Thannen, M., Smutny, R., Lampalzer, T., Strauss, A., & Rauch, H. P. (2019). Development of LCA benchmarks for Austrian torrent control structures. *The International Journal of Life Cycle Assessment*, 24(11), 2035–2053. <https://doi.org/10.1007/s11367-019-01618-6>
- Parliamentary Commissioner for the Environment. (2002). *Creating our Future—Sustainable development for New Zealand*. Available for download at:
<https://pce.parliament.nz/publications/archive/1997-2006/creating-our-future-sustainable-development-for-new-zealand/>

- Paulillo, A., Clift, R., Dodds, J. M., Milliken, A., Palethorpe, S. J., & Lettieri, P. (2020). Radiological impacts in Life Cycle Assessment. Part I: General framework and two practical methodologies. *Science of The Total Environment*, 708, 135179.
<https://doi.org/10.1016/j.scitotenv.2019.135179>
- Pelletier, N. (2017). Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. *Journal of Cleaner Production*, 152, 167–180.
<https://doi.org/10.1016/j.jclepro.2017.03.050>
- Pelton, R. E. O., & Smith, T. M. (2015). Hotspot Scenario Analysis. *Journal of Industrial Ecology*, 19(3), 427–440. <https://doi.org/10.1111/jiec.12191>
- Pinto-Bazurco, J. F. (2022). How to Enforce the Polluter-Pays Principle. *Policy Brief Number 31*. Available for download at: <https://www.iisd.org/articles/polluter-pays-principle>
- Planet Score. (2022). *Planet-score—Take care of the planet while shopping*. Planet-Score.
<https://www.planet-score.org/en/> (Accessed 20 December 2024)
- Ponte, S., & Cheyns, E. (2013). Voluntary standards, expert knowledge and the governance of sustainability networks. *Global Networks*, 13(4), 459–477.
<https://doi.org/10.1111/glob.12011>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. Scopus®.
<https://doi.org/10.1126/science.aaq0216>
- Porter, J., Xie, L., Challinor, A., Cochrane, K., Howden, S., Iqbal, M., Lobell, D., & Travasso, M. (2014). *Food Security and Food Production Systems* (Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge University Press. <https://www.ipcc.ch/report/ar5/wg2/>
- Prieto-Sandoval, V., Alfaro, J. A., Mejía-Villa, A., & Ormazabal, M. (2016). Eco-labels as a multidimensional research topic: Trends and opportunities. *Journal of Cleaner Production*, 135, 806–818. <https://doi.org/10.1016/j.jclepro.2016.06.167>
- Pure Advantage. (2012). *New Zealand's Position in the Green Race*. Available for download at <https://pureadvantage.org/green-growth-opportunities-for-nz/>
- Rainville, A. (2022). Green Public Procurement in Mission-Orientated Innovation Systems: Leveraging Voluntary Standards to Improve Sustainability Performance of Municipalities. *Sustainability*, 14(14), Article 14. <https://doi.org/10.3390/su14148591>

- Ranganathan, J., Waite, R., Searchinger, T., & Hanson, C. (2018). *How to Sustainably Feed 10 Billion People by 2050, in 21 Charts*. <https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts> (Accessed 21 December 2024)
- Repar, N., Jan, P., Dux, D., Nemecek, T., & Doluschitz, R. (2017). Implementing farm-level environmental sustainability in environmental performance indicators: A combined global-local approach. *Journal of Cleaner Production*, 140, 692–704. <https://doi.org/10.1016/j.jclepro.2016.07.022>
- Rockström, J., Edenhofer, O., Gaertner, J., & DeClerck, F. (2020). Planet-proofing the global food system. *Nature Food*, 1(1), 3–5. <https://doi.org/10.1038/s43016-019-0010-4>
- Ruggeri Laderchi, C., Lotze-Campen, H., DeClerck, F., Bodirsky, B. L., Collignon, Q., Crawford, M. S., Dietz, S., Fesenfeld, L., Hunecke, C., Leip, D., Lord, S., Lowder, S., Nagenborg, S., Pilditch, T., Popp, A., Wedl, I., Branca, F., Fan, S., Fanzo, J., ... Songwe, V. (2024). *The Economics of the Food System Transformation. Food System Economics Commission (FSEC), Global Policy Report*. Available for download at: <https://foodsystemeconomics.org/policy/global-policy-report/>
- Saarinen, M., Fogelholm, M., Tahvonen, R., & Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, 149, 828–844. <https://doi.org/10.1016/j.jclepro.2017.02.062>
- Sabaté, J. (2019). Connecting Health and Nutrition. In Joan, S. (Ed.) *Environmental Nutrition* (p. xv). Elsevier. <https://doi.org/10.1016/B978-0-12-811660-9.09987-2>
- Sachs, J. D., Lafortune, G., & Fuller, G. (2024). *The SDGs and the UN Summit of the Future. Sustainable Development Report 2024*. Dublin: Dublin University Press. <https://www.tara.tcd.ie/handle/2262/108572>
- Sachs, J. D., Lafortune, G., Fuller, G., & Iablonovski, G. (2025). *Sustainable Development Report 2025. Financing Sustainable Development to 2030 and Mid-Century*. Dublin University Press. <https://doi.org/10.25546/111909>
- Sala, S., Anton, A., McLaren, S. J., Notarnicola, B., Saouter, E., & Sonesson, U. (2017). In quest of reducing the environmental impacts of food production and consumption. *Journal of Cleaner Production*, 140, 387–398. <https://doi.org/10.1016/j.jclepro.2016.09.054>
- Salazar T, M. B., Cai, H., Bailey, R., & Huang, J.-Y. (2019). Defining nutritionally and environmentally healthy dietary choices of omega-3 fatty acids. *Journal of Cleaner Production*, 228, 1025–1033. <https://doi.org/10.1016/j.jclepro.2019.04.359>

- Satta, M., Passarini, F., Cespi, D., & Ciacchi, L. (2024). Advantages and drawbacks of life cycle assessment application to the pharmaceuticals: A short critical literature review. *Environmental Science and Pollution Research International*.
<https://doi.org/10.1007/s11356-024-33964-w>
- Saxe, H., Jensen, J. D., Bølling Laugesen, S. M., & Bredie, W. L. P. (2019). Environmental impact of meal service catering for dependent senior citizens in Danish municipalities. *The International Journal of Life Cycle Assessment*, 24(4), 654–666.
<https://doi.org/10.1007/s11367-018-1487-z>
- Schaubroeck, T., Ceuppens, S., Luong, A. D., Benetto, E., De Meester, S., Lachat, C., & Uyttendaele, M. (2018). A pragmatic framework to score and inform about the environmental sustainability and nutritional profile of canteen meals, a case study on a university canteen. *Journal of Cleaner Production*, 187, 672–686. <https://doi.org/10.1016/j.jclepro.2018.03.265>
- Schleifer, P., Brandi, C., Verma, R., Bissinger, K., & Fiorini, M. (2022). Voluntary standards and the SDGs: Mapping public-private complementarities for sustainable development. *Earth System Governance*, 14, 100153. <https://doi.org/10.1016/j.esg.2022.100153>
- Schleifer, P., Fiorini, M., & Auld, G. (2019). Transparency in transnational governance: The determinants of information disclosure of voluntary sustainability programs. *Regulation & Governance*, 13(4), 488–506. <https://doi.org/10.1111/rego.12241>
- Schleifer, P., & Sun, Y. (2020). Reviewing the impact of sustainability certification on food security in developing countries. *Global Food Security*, 24, 100337.
<https://doi.org/10.1016/j.gfs.2019.100337>
- Schmidt Rivera, X. C., Espinoza Orias, N., & Azapagic, A. (2014). Life cycle environmental impacts of convenience food: Comparison of ready and home-made meals. *Journal of Cleaner Production*, 73, 294–309. <https://doi.org/10.1016/j.jclepro.2014.01.008>
- Schouten, G., & Glasbergen, P. (2011). Creating legitimacy in global private governance: The case of the Roundtable on Sustainable Palm Oil. *Ecological Economics*, 70(11), 1891–1899.
<https://doi.org/10.1016/j.ecolecon.2011.03.012>
- Schouten, G., Toonen, H., & Leeuwerik, D. (2022). Input Legitimacy of Voluntary Sustainability Standards and Acceptance Among Southern Producers: A Qualitative Comparative Analysis. *Global Environmental Politics*, 22(3), 104–135.
- Schwarz, A. E., Herlaar, S., Cohen, Q. M., Quik, J. T. K., Golkaram, M., Urbanus, J. H., van Emmerik, T. H. M., & Huijbregts, M. A. J. (2024). Microplastic aquatic impacts included in Life Cycle

- Assessment. *Resources, Conservation and Recycling*, 209, 107787.
<https://doi.org/10.1016/j.resconrec.2024.107787>
- Seidel-Sterzik, H. (2019). *Bridging the barriers to effective life cycle management uptake: A framework for primary industry sectors*. [Doctoral dissertation, Massey University, New Zealand]. Massey Research Online <https://mro.massey.ac.nz/items/1d1ee697-9c9a-4e26-8cea-6d27288a0f57>.
- Seidel-Sterzik, H., McLaren, S., & Garnevska, E. (2018). Effective Life Cycle Management in SMEs: Use of a Sector-Based Approach to Overcome Barriers. *Sustainability*, 10(2), 359.
<https://doi.org/10.3390/su10020359>
- Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., & Witthöft, C. (2017). Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. *Journal of Cleaner Production*, 140, 470–478. <https://doi.org/10.1016/j.jclepro.2016.06.115>
- Sonnemann, G., Gemechu, E. D., Sala, S., Schau, E. M., Allacker, K., Pant, R., Adibi, N., & Valdivia, S. (2018). Life Cycle Thinking and the Use of LCA in Policies Around the World. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 429–463). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_18
- Sonnemann, G., & Margni, M. (Eds.). (2015). *Life Cycle Management*. Springer Netherlands.
<https://doi.org/10.1007/978-94-017-7221-1>
- Springmann, M., Clark, M., Mason-D'Croz, D., Weibe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H. C. J., Tilman, D., Rockström, J., Willett, W. (2018a). Options for keeping the food system within environmental limits. *Nature*, 562 (7728), 519-525. <https://doi-org.ezproxy.massey.ac.nz/10.1038/s41586-018-0594-0>
- Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M., & Scarborough, P. (2018b). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level detail. *The Lancet Planetary Health*, 2(10), e451–e461. [https://doi.org/10.1016/S2542-5196\(18\)30206-7](https://doi.org/10.1016/S2542-5196(18)30206-7)
- Starck, C. S., Blumfield, M., Keighley, T., Marshall, S., Petocz, P., Inan-Eroglu, E., Abbott, K., Cassettari, T., Ali, A., Wham, C., Kruger, R., Kira, G., & Fayet-Moore, F. (2021). Nutrient Dense, Low-Cost Foods Can Improve the Affordability and Quality of the New Zealand Diet—A Substitution Modeling Study. *International Journal of Environmental Research and Public Health*, 18(15), 7950. <https://doi.org/10.3390/ijerph18157950>

- Stenton-Dozey, J. M. E., Heath, P., Ren, J. S., & Zamora, L. N. (2021). New Zealand aquaculture industry: Research, opportunities and constraints for integrative multitrophic farming. *New Zealand Journal of Marine and Freshwater Research*, 55(2), 265–285. <https://doi.org/10.1080/00288330.2020.1752266>
- Stratton, A. E., Finley, J. W., Gustafson, D. I., Mitcham, E. J., Myers, S. S., Naylor, R. L., Otten, J. J., & Palm, C. A. (2021). Mitigating sustainability tradeoffs as global fruit and vegetable systems expand to meet dietary recommendations. *Environmental Research Letters*, 16(5), 055010. <https://doi.org/10.1088/1748-9326/abe25a>
- Sustainable Biomass Programme. (2020). *Standards Development Process: Sustainability Certification Landscape*. https://sbp-cert.org/wp-content/uploads/2020/05/Sustainability-Certification-Landscape-v1_FINAL.pdf
- Swinburn, B. A., Kraak, V. I., Allender, S., Atkins, V. J., Baker, P. I., Bogard, J. R., Brinsden, H., Calvillo, A., De Schutter, O., Devarajan, R., Ezzati, M., Friel, S., Goenka, S., Hammond, R. A., Hastings, G., Hawkes, C., Herrero, M., Hovmand, P. S., Howden, M., ... Dietz, W. H. (2019). The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report. *The Lancet*, 393(10173), 791–846. [https://doi.org/10.1016/S0140-6736\(18\)32822-8](https://doi.org/10.1016/S0140-6736(18)32822-8)
- Takacs, B., Stegemann, J. A., Kalea, A. Z., & Borrion, A. (2022). Comparison of environmental impacts of individual meals—Does it really make a difference to choose plant-based meals instead of meat-based ones? *Journal of Cleaner Production*, 379, 134782. <https://doi.org/10.1016/j.jclepro.2022.134782>
- Tao, J., Li, L., & Yu, S. (2018). An innovative eco-design approach based on integration of LCA, CAD\CAE and optimization tools, and its implementation perspectives. *Journal of Cleaner Production*, 187, 839–851. <https://doi.org/10.1016/j.jclepro.2018.03.213>
- Tayleur, C., Balmford, A., Buchanan, G. M., Butchart, S. H. M., Corlet Walker, C., Ducharme, H., Green, R. E., Milder, J. C., Sanderson, F. J., Thomas, D. H. L., Tracewski, L., Vickery, J., & Phalan, B. (2018). Where are commodity crops certified, and what does it mean for conservation and poverty alleviation? *Biological Conservation*, 217, 36–46. <https://doi.org/10.1016/j.biocon.2017.09.024>
- Testa, F., Iraldo, F., Vaccari, A., & Ferrari, E. (2015). Why Eco-labels can be Effective Marketing Tools: Evidence from a Study on Italian Consumers. *Business Strategy and the Environment*, 24(4), 252–265. <https://doi.org/10.1002/bse.1821>

- Thorlakson, T., Hainmueller, J., & Lambin, E. F. (2018). Improving environmental practices in agricultural supply chains: The role of company-led standards. *Global Environmental Change*, 48, 32–42. <https://doi.org/10.1016/j.gloenvcha.2017.10.006>
- Torelli, R., Balluchi, F., & Lazzini, A. (2020). Greenwashing and environmental communication: Effects on stakeholders' perceptions. *Business Strategy & the Environment (John Wiley & Sons, Inc)*, 29(2), 407–421. <https://doi.org/10.1002/bse.2373>
- Tukker, A., Emmert, S., Charter, M., Vezzoli, C., Sto, E., Munch Andersen, M., Geerken, T., Tischner, U., & Lahlou, S. (2008). Fostering change to sustainable consumption and production: An evidence based view. *Journal of Cleaner Production*, 16(11), 1218–1225. <https://doi.org/10.1016/j.jclepro.2007.08.015>
- UNEP. (2010). *ABC OF SCP: Clarifying concepts on Sustainable Consumption and Production*. https://sustainabledevelopment.un.org/content/documents/945ABC_ENGLISH.pdf
- UNEP. (2024). *Eco-labelling*. <https://www.unep.org/explore-topics/resource-efficiency/what-we-do/responsible-industry/eco-labelling> (Accessed 17 January 2025)
- UNFCCC. (2024a). *The Paris Agreement*. <https://unfccc.int/process-and-meetings/the-paris-agreement?> (Accessed 4 January 2025)
- UNFCCC. (2024b). *What is the Kyoto Protocol?* https://unfccc.int/kyoto_protocol (Accessed 4 January 2025)
- UNFSS. (2012). *Voluntary Sustainability Standards: Today's landscape of issues & initiatives to achieve public policy objectives. Part 2*. https://unfss.org/wp-content/uploads/2012/05/unfss-report-initiatives-2_draft_lores.pdf
- UNFSS, FAO, ITC, UNCTAD, UNEP, & UNDO. (2020). *Scaling up Voluntary Sustainability Standards through Sustainability Public Procurement and Trade Policy*. https://unctad.org/system/files/official-document/unfss_4th_2020_en.pdf
- UNICEF. (2022). *Front-of-pack nutrition labelling of foods and beverages*. Available for download at: <https://www.unicef.org/mongolia/documents/front-pack-nutrition-labelling-foods-and-beverages>
- United Nations. (2021). *Action Tracks*. <https://www.un.org/en/food-systems-summit/action-tracks> (Accessed 7 August 2024)
- United Nations. (2023a). *The Sustainable Development Goals Report. Special edition. Towards a Rescue Plan for People and Planet*. <https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf>

- United Nations. (2023b). *UN Climate Change Conference—United Arab Emirates / UNFCCC*.
<https://unfccc.int/cop28> (Accessed 3 August 2024)
- United Nations. (2024a). *United Nations Conference on Environment and Development, Rio de Janeiro, Brazil, 3-14 June 1992*. <https://www.un.org/en/conferences/environment/rio1992>
 (Accessed 3 August 2024)
- United Nations (2024b). *Global Issues: Population*. United Nations; United Nations.
<https://www.un.org/en/global-issues/population> (Accessed 3 August 2024)
- United Nations Department of Economic and Social Affairs. (2015). *Transforming our world: The 2030 agenda for sustainable development (A/RES/70/1)*.
<https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981> (Accessed 3 August 2024)
- United Nations Department of Economic and Social Affairs. (2024a). *Goal 2 End hunger, achieve food security and improved nutrition and promote sustainable agriculture*.
<https://sdgs.un.org/goals/goal2> (Accessed 3 August 2024)
- United Nations Department of Economic and Social Affairs. (2024b). *Goal 12 Ensure sustainable consumption and production patterns. Targets and indicators*.
https://sdgs.un.org/goals/goal12#targets_and_indicators (Accessed 15 December 2024)
- United Nations Economic and Social Council. (2023). *Progress report on the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns*. Available for download at: <https://www.unep.org/resources/report/progress-report-10-year-framework-programmes-sustainable-consumption-and>
- Ulrich, S. C., & Handley, S. J. (2020). From ‘clean and green’ to ‘brown and down’: A synthesis of historical changes to biodiversity and marine ecosystems in the Marlborough Sounds, New Zealand. *Ocean & Coastal Management*, 198, 105349.
<https://doi.org/10.1016/j.ocecoaman.2020.105349>
- van der Kloet, J. (2011). *Transnational Supermarket Standards in Global Supply Chains The Emergence and Evolution of Global GAP* (Nijmegen Sociology of Law Working Papers Series 2011/03). Radboud University Nijmegen. <https://repository.ubn.ru.nl/handle/2066/91384>
- van der Ven, H. (2022). Effects of stakeholder input on voluntary sustainability standards. *Global Environmental Change*, 75, 102554.
<https://doi.org/10.1016/j.gloenvcha.2022.102554>

- van der Ven, H., & Barmes, D. (2023). The uneasy marriage of private standards and public policies for sustainable commodity governance. *Business Strategy and the Environment*, n/a(n/a). <https://doi.org/10.1002/bse.3424>
- van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, 2(7), 494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Von Braun, J., Afsana, K., Fresco, L. O., Hassan, M. H. A., & Torero, M. (2023). Food system concepts and definitions for science and political action. In J. Von Braun, K. Afsana, L. O. Fresco, & M. H. A. Hassan (Eds.), *Science and Innovations for Food Systems Transformation* (pp. 11–17). Springer International Publishing. <https://doi.org/10.1007/978-3-031-15703-5>
- Veale, M., Renard, N., & Seixas, R. (2015). *Moving to metrics: Opportunities and challenges of performance-based sustainability standards*. Available for download at: <https://discovery.ucl.ac.uk/id/eprint/1474248/>
- Veldhuizen, L. J. L., Giller, K. E., Oosterveer, P., Brouwer, I. D., Janssen, S., van Zanten, H. HE., & Slingerland, M. A. (2020). The Missing Middle: Connected action on agriculture and nutrition across global, national and local levels to achieve Sustainable Development Goal 2. *Global Food Security*, 24, 100336. <https://doi.org/10.1016/j.gfs.2019.100336>
- Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. I. (2012). Climate Change and Food Systems. *Annual Review of Environment and Resources*, 37(1), 195–222. <https://doi.org/10.1146/annurev-environ-020411-130608>
- Viart, N., Seixas, R., & Slavinski, S. (2016). *Evaluation of the Bonsucro calculator as a sustainability performance benchmarking tool in the sugarcane sector*. <https://www.bsst.uk/papers/papers/2017agm3.pdf>
- von Geibler, J. (2013). Market-based governance for sustainability in value chains: Conditions for successful standard setting in the palm oil sector. *Journal of Cleaner Production*, 56, 39–53. <https://doi.org/10.1016/j.jclepro.2012.08.027>
- Wainwright, H., Jordan, C., & Day, H. (2014). Environmental Impact of Production Horticulture. In G. R. Dixon & D. E. Aldous (Eds.), *Horticulture: Plants for People and Places, Volume 1* (pp. 503–522). Springer Netherlands. https://doi.org/10.1007/978-94-017-8578-5_15
- Wang, C., Ghadimi, P., Lim, M. K., & Tseng, M.-L. (2019). A literature review of sustainable consumption and production: A comparative analysis in developed and developing

- economies. *Journal of Cleaner Production*, 206, 741–754.
<https://doi.org/10.1016/j.jclepro.2018.09.172>
- Wartella, E. A., Lichtenstein, A. H., & Boon, C. S. (2010). *Examination of Front-of-Package Nutrition Rating Systems and Symbols: Phase I Report*. Available for download at:
<https://pubmed-ncbi-nlm-nih-gov.ezproxy.massey.ac.nz/24983042/>
- WBSCD. (2021). *Food Labeling: Principles to support the uptake of healthy and sustainable diets*. Available for download at: <https://www.wbcsd.org/resources/principles-to-support-the-uptake-of-healthy-and-sustainable-diets/>
- WHO. (2024). *Fact sheets—Malnutrition*. <https://www.who.int/news-room/fact-sheets/detail/malnutrition> (Accessed 2 January 2025)
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., ... Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Withers, P. J. A., Neal, C., Jarvie, H. P., & Doody, D. G. (2014). Agriculture and Eutrophication: Where Do We Go from Here? *Sustainability*, 6(9), Article 9.
<https://doi.org/10.3390/su6095853>
- World Health Organization (WHO). (2023). *Total fat intake for the prevention of unhealthy weight gain in adults and children: WHO guideline*. Available for download at:
<https://www.who.int/publications/i/item/9789240073654>
- Yan, H. F., Kyne, P. M., Jabado, R. W., Leeney, R. H., Davidson, L. N. K., Derrick, D. H., Finucci, B., Freckleton, R. P., Fordham, S. V., & Dulvy, N. K. (2021). Overfishing and habitat loss drive range contraction of iconic marine fishes to near extinction. *Science Advances*, 7(7), eabb6026. <https://doi.org/10.1126/sciadv.abb6026>
- Zu, L. (2013). Sustainable Production and Consumption. In S. O. Idowu, N. Capaldi, L. Zu, & A. D. Gupta (Eds.), *Encyclopedia of Corporate Social Responsibility* (pp. 2474–2482). Springer.
https://doi.org/10.1007/978-3-642-28036-8_258

Chapter 2 Potential for a life cycle-based VSS in the New Zealand avocado sector

This chapter introduces the New Zealand avocado sector. After outlining its structure and performance (Section 2.1), the enablers and barriers to adoption of agri-food VSS are reviewed (Section 2.2). Section 2.3 reports the methods used for a perception-based qualitative study to understand stakeholder perspectives about the sector's current sustainability pursuits, possible motivations to adopt a life cycle-based VSS and potential challenges. The main learnings are summarised in Section 2.4, followed by a discussion on these insights in Section 2.5. Section 2.6 concludes the chapter. The following sections are being drafted for journal submission.

2.1 The New Zealand avocado sector

New Zealand's primary industry, mainly comprising food and fibre sectors, accounts for >80% of total national goods exports, and has a \$57 billion export revenue forecasted for mid-2025 (MPI, 2024). The primary industry has traditionally been driven by dairy, meat & wool, and forestry (MPI, 2020; Nana, 2010). However, the New Zealand's ~ \$7.5 billion export-driven horticultural sectors spread across 80,000 hectares are now collectively considered the 'fourth engine' of the country's primary industry (ASB Bank, 2018; Horticulture New Zealand, 2024). While kiwifruit, wine, and apples continue to lead horticultural production in terms of export value (\$2.6 billion, \$2.4 billion, and >\$892 million in 2023) (New Zealand Apples and Pears, 2024a; New Zealand Wine, 2023; United Fresh, 2023), growth in the New Zealand avocado sector has been particularly pronounced. In 2023, > 1000 growers in New Zealand produced ~38 million tonnes of avocados across 5000 hectares. The total value of the avocado sector to New Zealand was >\$122 million in 2023, of which ~\$61.5 million was from exports; this is an increase of >140% from 2000 and ~102% over the last decade (Table 2.1).

Avocados are grown in three main regions in New Zealand: the Bay of Plenty, Far North and Mid-North (collectively known as Northland) (New Zealand Avocado, 2024a). The Bay of Plenty has

traditionally accounted for >60% of the avocados grown in New Zealand, but with recent large-scale plantings in the Far North, it now accounts for 50% of the total planted area, while 45% lies in Northland, and the remaining 5% spread across other parts of New Zealand (New Zealand Herald, 2025). Avocados are packed at 13 packaging and coolstore facilities in the Bay of Plenty and Northland. They are exported to 11 markets, of which Australia has been the main market for several years. However, the industry sector has been increasingly diversifying its export market base, which now includes several countries in Asia (United Fresh, 2023). With respect to future growth, many dairy farms are being converted to avocado orchards, and hundreds of new ongoing and planned plantings are planned or in progress, especially in Northland (Chalmers, 2019; Stringleman, 2023).

Table 2.1 Production volume (in 5.5 kg TEs¹⁵) and value (in New Zealand) of New Zealand-grown avocados (Source: NZ Avocado, 2023a)

Year	Total Production Volume (5.5 kg TEs in '000s)	Total Volume Exported (Fresh) (5.5 kg TEs, '000s)	Total Production Value (New Zealand, 000s)	Total Export Value (Fresh) (New Zealand, 000s)
2022-23	6,906	2,655	122,395	61,496
2021-22	8,253	3,914	120,919	61,867
2020-21	8,237	4,811	233,619	167,863
2019-20	7,105	3,617	154,054	99,167
2018-19	5,713	2,979	144,142	85,528
2017-18	4,110	2,235	152,115	104,675
2016-17	7,886	4,732	200,345	155,545
2015-16	4,165	2,551	133,907	91,421
2014-15	7,110	4,488	134,614	101,329
2013-14	4,897	3,137	135,886	102,859
2012-13	2,568	1,217	60,448	31,667

¹⁵ A TE is a standard measure of avocado quantities in New Zealand determined for levy purposes and equals 5.5 kg of fruit.

The New Zealand avocado sector is represented by the industry association New Zealand Avocado, which promotes the marketing and consumption of New Zealand-grown avocados, runs a research and development programme, disseminates relevant information about the sector, and lobbies/liaises with the government on behalf of the sector. New Zealand Avocado is a primarily levy-funded organisation under the Commodity Levies (Avocados) Order 2019. The association also actively obtains external funding for development projects, with over 60% Crown investment, through cash and in-kind. The Primary Growth Partnership (PGP), driven by New Zealand's Ministry for Primary Industries (MPI) is a joint venture between the public and industry sectors, which helps primary sectors succeed via long-term investments in innovative programmes. In the recent past, NZ Avocado was a signatory to the PGP via its Go Global programme, a \$11.4 million 7-year venture (ended December 2021). The main aim of the Go Global programme was to reduce the New Zealand avocado sector's reliance on its single largest market (Australia) and transform it into 'a sustainable, high-value export sector' (NZ Avocado, 2025). Its projects ranged from digitising avocado supply chains, to investigating an avocado breeding programme, and developing the sector's sustainability credentials (Maven Consulting Ltd, 2024). One of NZ Avocado's most significant sustainability activities to date is the AvoGreen pest monitoring and management programme. An auditable system, it is grounded in the Integrated Pest Management (IPM) system – an internationally accepted set of principles to ensure that the use of pesticide and other chemical sprays are limited and applied only when necessary. All avocado growers are required by law to comply with AvoGreen principles and stipulations, if they wish to export their fruit.

Thus, the New Zealand avocado sector is a suitable case study sector for this research because it is strong, cohesive, proactive, and fast-growing. It has also recognised the relevance of demonstrating its sustainability credentials and is committed to continuous improvement in its sustainability profile. Examples of this commitment include its commissioning of a

comprehensive sector-wide LCA study (NZ Avocado, 2023b) and its recently developed 'Respectful Harvest' framework which aims for nutritious avocado production using good agricultural and agrichemical practices, and optimal harvest times (NZ Avocado, 2024b).

2.2 Review of literature on VSS enablers and barriers

The success dimensions of a VSS-based certification scheme include their problem-solving effectiveness (to what extent the aims of the standard were met, problems solved, and behavioural changes facilitated), adoption and market diffusion, and the closely related concepts of stakeholder acceptance or legitimacy (Tröster, 2018). The problem-solving dimension is not the focus of the qualitative study in this chapter, rather it aims to understand the potential for VSS uptake in the sector (Section 2.3).

This section reviews the literature on VSS in order to determine factors that can affect the perceived legitimacy and subsequent uptake of a VSS in an agri-food sector. Known as 'VSS adoption determinants' (Brandi et al., 2015), addressing these perception-based¹⁶ insights from relevant stakeholders about the enablers (including their drivers, motivations, and perceived benefits) as well as potential barriers (hesitations and perceived challenges) can increase the effectiveness of uptake of VSS.

A literature review was conducted to identify the potential adoption determinants that might be appropriate for the New Zealand context. First, a search was conducted on Scopus and Google Scholar using the search terms (agri-food) OR (agrifood) OR (agricultur*) OR (horticultur*) OR (food)' AND (Voluntary Sustainability Standard*) OR (VSS) OR (ecolabel*}'. Results were limited

¹⁶ 'Perception-based research' is a mode of inquiry which evaluates the attitudes, opinions, and views of stakeholders (individual or in a group) about a particular phenomenon or situation to understand it better. As Fred et al. (2022) note, the adoption of sustainability initiatives is directly related to stakeholder attitudes towards sustainability, and how they perceive those initiatives. Therefore, an understanding of those perspectives is essential to the success of such initiatives.

to years from 2000-2025, and to English language sources. The questionnaire for the qualitative study was informed by literature up to 2019, as that was the year when the study was conducted. This search resulted in 468 studies. The abstracts of these studies were assessed to identify only those which specifically looked at VSS adoption. This resulted in a shortlist of 51 papers, which were then categorised by VSS, sector, country, and main findings.

It was found that certain agri-food VSS like RSPO, Global G.A.P. (including nationally benchmarked G.A.P. schemes like PhilGAP and ThaiGAP), Fairtrade, Rainforest Alliance, and SWNZ were most frequently studied, while a few studies also looked at the Aquaculture Stewardship Council (ASC), Marine Stewardship Council, (MSC), UTZ, and 4C. Some mainstream VSS such as Bonsucro, LEAF Marque, Red Tractor, Proterra, and Protected Harvest, were absent. Fresh produce (fruits and vegetables), palm oil, coffee, and wine were the most studied sectors, with only a limited number of studies on cacao, dairy, beef, soy, aquaculture, and fisheries. Some sectors like tea, sugarcane, floriculture, and arable crops were not present. Of the 51 papers, the majority (n=41) looked at developing countries, with an overwhelming focus on smallholders. For example, incentives and constraints for smallholders growing coffee in Guatemala, Costa Rica and Colombia (Grabs et al., 2016), fruit in Ghana (Quartey et al., 2021) and Peru (Lemeilleur, 2013), vegetables in Kenya (Chelang'a et al., 2023; Kariuki, 2014) and Malaysia (Tey et al., 2015), and oil palm in Thailand, Malaysia, Ghana, and Indonesia (Irawan et al., 2024; Npueng et al., 2023; Pongthong & Masahiro, 2014; Rietberg, 2016). Only 10 studies addressed VSS adoption in developed countries (Spain, Italy, Germany, USA, Ireland, and New Zealand). A review of the findings of all 51 studies found a considerable difference between the factors driving/inhibiting VSS uptake in developed versus developing countries (Table 2.2).

Table 2.2 Determinants of agri-food VSS adoption in developed and developing countries identified in the literature review

Category	Adoption determinant	Developed Countries	Developing Countries
Financial/marketing	Business advantages (Price premiums, higher sales and profit margins, competitive advantage/market differentiation/market access/ready market availability/increased market share)	✓	✓
	Reputation	✓	
	Image/brand equity	✓	
	Costs (Certification and audit costs, technological innovation to meet requirements)	✓	✓
	Cost benefits (related to input and operational efficiency, higher product quality, productivity etc.)	✓	✓
	Off-farm income		✓
	Economies of scale	✓	✓
	Financial incentives (e.g. government subsidies)		✓
Business operations	Process/operational efficiency	✓	
	Capacity building		✓
	Employee education, motivation, retention, becoming a better/more attractive employer	✓	
Access to resources/support	Governance structure and institutional infrastructure		✓
	Access to support from government, facilitators, exporters, and extension services		✓
	Access to resources – funds, high quality seedlings, fertilisers etc.		✓
Knowledge	Knowledge expansion for sustainable growth	✓	
	Skills, and technical know-how	✓	✓
	Knowledge sharing/transfer/communicating and increasing awareness	✓	✓
	Awareness of VSS details (training)		✓
Farm and grower characteristics	Household factors (number of members, number of males, level of education)		✓
	Farm size and age		✓
	Age and experience of grower		✓
	Land titles and rights		✓

	Other farm and livestock assets		✓
Standard characteristics	Measurable performance metrics like GHG emissions for continuous improvement	✓	
	Complexity of the standard	✓	✓
	Appropriateness/comprehensiveness of sustainability requirements of VSS	✓	
	Appropriateness (national, sectoral, practice contexts)	✓	
	Flexibility of VSS		✓
Perceptions about VSS effectiveness	Perceived effectiveness of VSS adoption	✓	✓
	Perceived necessity for changes towards sustainability	✓	
Ethical aspects	Moral compass – ‘Right thing to do’	✓	
	Environmental benefits/concern about environmental issues/socio-environmental responsibility/stewardship	✓	
Supply chain factors	Supply chain transparency, transaction risk reduction, improved collaboration with suppliers	✓	
	Industry/sector support and recognition	✓	
	Demand from retailers, consumers, and other institutional stakeholders	✓	✓
	Share of costs along value chain	✓	✓
	Trust within value chain		✓
	Fragmentation/vertical integration of value chain actors/availability of contracts		✓
	Membership and participation in grower groups, and co-operatives	✓	✓
	Inclusion/participation of actors from developing countries in VSS owned and operated by developed countries		✓
Others	Industry/sector incentives like events and awards restricted to participating growers	✓	
	Voluntary standards becoming de facto mandatory	✓	✓
	Current and future legislative requirements	✓	✓
	Time and administrative investment	✓	
	Socio-political factors		✓
	Risk-taking capability		✓

Some of the determinants of VSS adoption are common to both developed and developing countries. These include cost of audit and certification, and technological innovation required for certification, market and institutional demands, competitive advantages like market differentiation, market access, and price premiums, and legislative requirements. However, there are determinants which are unique to and relevant only to developing countries. For example, household variables like size, number of male members and level of education; the degree of contact with and support from extension centres¹⁷; access to government funding and institutional support; organization of farmer's groups; access to high quality farm inputs like seedlings, pesticides, and fertilisers; complexities around land titles and VSS conditions about land use; threats from cartels; availability of financial resources and technical knowledge; and highly nuanced socio-cultural norms and traditions (e.g. Brandi et al., 2015; Chelang'a et al., 2023; de Vos et al., 2023; Djokoto et al., 2015; Fred et al., 2022; Kariuki, 2014; Npueng et al., 2023; Pongthong & Masahiro, 2014; Quartey et al., 2021; Rietberg, 2016; Rodthong et al., 2023). Since New Zealand is a developed country, these factors are not applicable to the New Zealand context.

Of the studies looking at developed countries, five considered VSS in New Zealand, and one each in Germany, Ireland, Spain, Italy, and USA (California). Overall, the studies found that business and economic benefits like sales growth, market differentiation and consequent consumer favour, price premiums, and market access provided a competitive advantage favourable to VSS adoption. For example, Lees (2020) noted that Origin Green offers growers the ability to stay competitive in a market that increasingly requires demonstrable sustainability credentials. The carbon footprint requirements of the scheme enable growers to better understand their

¹⁷ Agricultural extension refers to systems that are put in place to offer support in the form of skill development, technological knowhow and community participation (FAO, 2005). The extension services provided by centres in developing countries can vary significantly from those in developed nations in terms of infrastructure and support structure.

environmental performance, relative to industry benchmarks, and this supports continuous improvement in their performance. The resulting cumulative decrease in the industry's carbon footprint is a demonstrated sustainability credential, which differentiates the Origin Green brand in export markets. The consequent price premium from the market differentiation is also noted as a driver to uptake. Similarly, when the Sustainable Winegrowing New Zealand (SWNZ) programme was launched, it was driven by the sector's desire to be a global player in a fast-growing market. Thus, SWNZ adoption was largely driven by institutional stakeholder pressure aiming to differentiate New Zealand wine as a niche product on the basis of its quality and sustainability credentials (Sautier et al., 2018). The reputational benefits and profits that ensued increasingly drew more wineries to 'get on board' and soon, the certification became 'de facto mandatory'. Today 98% of wineries in New Zealand are SWNZ certified (New Zealand Wine, 2025).

Other business advantages (as enablers to adoption) include reduced transactional risks and increased collaboration with supply chain actors (Stranieri et al., 2021). In addition, concern for the environment and perceived environmental benefits, land stewardship, improved product quality, meeting export requirements, brand/image enhancement, and operational efficiency/process optimisation are also drivers to VSS uptake in developed countries (Dodds et al., 2013; Hannus & Sauer, 2021; Hughey et al., 2005; Lees, 2020; Nyblom, 2020; Pomarici et al., 2015). The main barriers included extensive time and cost involved for the audit and certification, and rigour of environmental practices required to be adopted for compliance, the perception that systems are already sustainable and additional practices do not add value, and the ambiguity around actual on-farm and business benefits of VSS adoption (Baird et al., 2018; Hannus & Sauer, 2021; Lees, 2020; Nyblom, 2020; Rosin et al., 2008). Irish farmers also voiced their concerns about all farmers in the Origin Green programme being treated equally, irrespective of the efforts made towards improvement; they were discouraged by the lack of market differentiation (and consequent price premiums) for those whose carbon footprints

were lower than others (Lees, 2020). The limited nature of sustainability requirements within VSS was also noted as a barrier to uptake (Nyblom, 2020).

Since only five New Zealand-based studies were identified in the literature review on VSS adoption determinants (four on wine and one on kiwifruit), a further search was done to identify research on the adoption of overall sustainability practices in New Zealand agri-food sectors. Six studies were identified in three sectors: dairy (Swallow & Barkemeyer, 2024), viticulture (Flint & Golicic, 2009; Gabzdylova et al., 2009; Wilson, 2011), and horticulture (De Silva & Forbes, 2016; Seidel-Sterzik, 2019). While these studies do not directly address the adoption of VSS, the enablers and barriers identified in them (with respect to sustainability practices in general) could potentially apply to VSS uptake. Similar findings to the review on VSS adoption were noted. For example, the enablers included the stakeholder perception of better product quality as a direct outcome of the practices, and pressure from governments, retailers and consumers in importing markets driving the uptake of sustainability measures. The barriers included the perceived high cost and time demands associated with implementing sustainable practices and concomitant low returns (De Silva & Forbes, 2016; Gabzdylova et al., 2009; Swallow & Barkemeyer, 2024). In addition, personal values (such as concern about the environment), the degree of occupational satisfaction, communication among stakeholders, the level of knowledge and expertise, and organizational/sectoral culture can also determine adoption intensity (Gabzdylova et al., 2009; Seidel-Sterzik et al., 2018; Wilson, 2011).

In addition to the enablers and barriers identified in the literature, further insights about research gaps were obtained from the review. First, 30 of the studies collected data from growers only while 11 obtained data from multiple stakeholders who provided their views on grower uptake of VSS. Of the latter, the majority (n=7) considered only horizontal actors associated with/supporting VSS implementation (e.g. facilitators, consultants, government representatives, industry associations, researchers, co-operatives, VSS representatives, donors, and NGOs). Vertical value chain stakeholders (e.g. post-harvest operators, exporters,

distributors, and retailers) were under-represented. Three studies included downstream stakeholders in the value chain in addition to horizontal actors (Coral & Mithöfer, 2022; Grabs et al., 2016; Wongprawmas et al., 2015), while one focused solely on fresh produce exporting companies in 10 African countries (Henson et al., 2011). Thus, there is a gap in the research on the perceptions of downstream value chain stakeholder regarding the adoption of agri-food VSS.

Second, most of the studies were ex-post analyses, i.e. they investigated the enablers of and barriers to adoption of VSS that are already operational. Only one study (Hannus & Sauer, 2021) used surveys and questionnaires to assess German farmers' preferences and perceived barriers regarding the adoption of a hypothetical, cross-sectoral sustainability standard. Questions included those related to farmer expertise and farming practices, how they perceived national agri-food sustainability, and their views on why they would adopt the standard (or not). Additionally, they were also asked questions about the design elements of a VSS to determine which ones they perceived as more important. The study identified process optimization, economic benefits, image enhancement, and environmental protection as the main drivers to adoption, and cost/time required for certification, complexities inherent in the standard, and the uncertainty regarding the actual/perceived usefulness of the scheme were identified as the main barriers to adoption.

One resource for ex- and post-ante analysis of VSS adoption by stakeholders was identified – the VSS Assessment Toolkit. The toolkit is a framework developed by the United Nations Centre for Trade and Development (UNCTAD) (UNCTAD, 2020) to *'guide the identification of the challenges and perceptions behind the adoption of a VSS scheme'*. It prominently features value chain mapping and interviews with relevant stakeholders to better understand their main challenges and motivations in VSS uptake. Examples of guidance questions within this toolkit include, *"When were you last certified, and did you pay to obtain the certification?"*; *"Are there many or few local producers who are certified in your area? Why is this so?"*; and *"Why did you stop participating in a certification scheme?"* Therefore, while it is not explicitly stated, it appears that

this toolkit was designed for VSS which have already been developed, i.e. undergone the standard-setting process, been implemented, and are currently in operation. However, some of the questions within the toolkit could potentially be adapted and used as a guideline for an ex-ante investigation into the adoption determinants of a VSS which is yet to be developed and implemented.

Third, with respect to the intersection between life cycle thinking (LCT) and VSS, this current review showed that no studies have so far investigated the adoption of a potential sector-based VSS based on life cycle considerations, or LCA-based criteria.

In summary, the literature review identified potential enablers and barriers to agri-food VSS uptake relevant to the New Zealand context. This informed the questionnaire development for the qualitative study reported in Sections 2.3-2.5. In addition, five research gaps were detected:

- Developed countries were largely under-represented in the literature, when compared with the large number of studies on developing countries.
- A large majority of the studies focused on grower motivations for adoption, by obtaining data from the growers themselves. Other stakeholders, particularly, downstream value chain stages were significantly under-represented.
- Most of the studies were ex-post, i.e., they considered existing VSS that have already been implemented. Only one investigated the enablers of and barriers to adoption of a hypothetical standard by German growers. However, it was focused on the farm-level and did not have a sectoral focus.
- There has been no research into the adoption of a potential sector-based VSS based on life cycle considerations, or LCA-based criteria.

2.3 Qualitative study on New Zealand avocado sector stakeholder perceptions: methodology

The main goal of this study was to gain a deeper understanding of the potential for the development and uptake of a life cycle-based VSS for the avocado sector in New Zealand.

Perception-based research inherently lends itself to qualitative methods like interviews. In particular, semi-structured interviews provide a framework for a rich and in-depth exploration of attitudes and perceptions as they allow respondents to share their views freely, within a certain degree of structure in the form of pre-determined questions. This method is more informal and conversational than structured interviews with yes/no or Likert scale answers – the questions guide the interviewer allowing for adjustments and adaptations based on responses, while ensuring that key topic areas are covered. This is why semi-structured interviews are a commonly used method in sustainability research, including research on the uptake of sustainability practices and standards like VSS (Baird et al., 2018; de Vos et al., 2023; Grabs et al., 2016; Kennedy et al., 2017; Lees, 2020; Rosin et al., 2008; Wongprawmas et al., 2015). Thus, for this current study, the semi-structured interview approach was chosen as the data collection method.

Two separate interview questionnaires were prepared: one for avocado growers and the other for downstream stakeholders in the avocado value chain (Appendix B). A list of questions was drawn up based on overarching common themes noted in literature relevant to this study and followed frameworks previously established in the literature (De Silva & Forbes, 2016; Dodds et al., 2013; Gabzdylova et al., 2009; Hughey et al., 2005; Secretario, 2017)¹⁸. The questionnaires for both growers and downstream stakeholders comprised three sections. The first section's purpose was to collection information about the general stakeholder profile. This was the only section that varied between the two questionnaires – one asked questions related to orchard location, production, type of fruit produced, etc. while the other focused on details about the packer/exporter, how much and what kind of fruit they process, how much is sold domestically versus exports, and so on, The second section included questions aimed at stakeholder perceptions about sustainability issues in the avocado sector, and current sustainability

¹⁸ The relevant literature used to develop the interview questionnaires spanned the period from 2000-2019 as the study was conducted in 2019. The literature review in Section 2.2 refers to additional literature post-2019 as well.

practices employed on their orchard or within their organisation. Such questions help to explore stakeholder orientations towards sustainability in general and help uncover their drivers and motivations in participating in these initiatives (Merfield et al., 2015). As these initiatives are usually voluntary, these questions help to predict how amenable they might be to adopt a newly developed VSS for the sector. The third section of the questionnaire deals with stakeholder perceptions about potential benefits to a new VSS scheme, especially one based on life cycle considerations. These include product differentiation and associated benefits like price premiums, reputational/image enhancement, brand development, more market opportunities, and actual sustainability impacts. The questions also probe possible challenges to uptake based on perception and experience (for example, time, costs, and administrative resources required for compliance and certification), and general insights into the structure of the scheme and how it might impact adoption. While other more in-depth purely qualitative research constructs and refines questions iteratively based on an initial pilot study and peer reviews/discussions (Secretario, 2017), this approach was not taken for the current study. The reason for this is that this qualitative study was meant to be a scoping study itself purely aimed at understanding motivations for adopting (or not) a new VSS in the avocado sector, as a foundation for the rest of the LCA-based research in this thesis. Therefore, for the scope of this study, it was deemed unnecessary to conduct follow up interviews with adjusted questions.

Purposive sampling was used in this study. This involves purposefully identifying and selecting individuals or groups of individuals who have expertise, experience in – and/or knowledge about the phenomenon being studied (Palinkas et al., 2015). In addition, purposive sampling also takes into consideration the availability of participants and their willingness to participate (Etikan et al., 2016). It was frequently used in the studies identified in the literature review (Chelang'a et al., 2023; Fred et al., 2022; Lemeilleur et al., 2020; Quartey et al., 2021), as well as other agri-food studies which employ semi-structured interviews to obtain qualitative perception-based data from participants (Johnson, 2022; Kusnezowa & Vang, 2021; Matt Reed et al., 2017; Rosin et al., 2024). Marshall (1996) says that an *“An appropriate sample size for a*

qualitative study is one that adequately answers the research question". Primary data were collected via 15 interviews with stakeholders along the New Zealand avocado value chain – including the industry association New Zealand Avocado, growers, harvesters and orchard managers, packers and exporters (Table 2.3). Of the 15 interviewees, 14 were based in the Tauranga region of the Bay of Plenty. During the course of the interviews, the researcher was also introduced to another grower in the Mid North, and a Skype interview was conducted with him as well to understand more about the new avocado plantations in Northland.

Table 2.3 Interviewee details obtained from 15 stakeholder interviews

Number	Interviewee	Region	Orchard Size/number of growers and packhouses supplying avocados	Avocados harvested for export / exported (kg/year)
1	Grower	Bay of Plenty	6.2 ha	60,500-66,000
2	Grower	Bay of Plenty	5.2 ha	60,500
3	Grower	Bay of Plenty	16 ha	110,000
4	Grower	Northland (Mid-North)	192.6 ha	1,650,000
5	Grower	Bay of Plenty	8 ha	82,500
6	Grower	Bay of Plenty	9.5 ha	126,500
7	Grower	Bay of Plenty	8.3 ha	66,000
8	Grower	Bay of Plenty	2 ha	2,750
9	Grower/Orchard manager	Bay of Plenty	Own – 5 ha; Managed – 30 ha	742,500
10	Grower/orchard manager	Bay of Plenty	Own orchard 2 ha; managed orchards 60 ha	Own orchard - NA*; Managed orchard – 825,000
11	Packhouse/orchard manager	Bay of Plenty	Pack from managed orchards – 20 ha; also pack avocados supplied by 180 other growers	1,650,000 packed
12	Grower, packer, exporter	Bay of Plenty	>100 ha (own and managed orchards)	NA**
13	Exporter	Bay of Plenty, Far North, Mid North	Supplied by 786 growers and 6 packhouses	8,250,000
14	Packer	Bay of Plenty and Far North	-	1,650,000
15	New Zealand Avocado	Bay of Plenty, Far North, Mid-North	-	-

**At the time of the interview, the grower had just planted the orchard and had not harvested any fruit for export yet; ** Disaggregated information unavailable at the time of interview*

The relevant ethics approval for the interview process was obtained from Massey University in alignment with the Massey University Human Ethics Code (MUHEC). Interviewees were contacted via email, providing the background to the study, asking for permission to conduct the interview, and providing assurance of anonymity and confidentiality. Interviewees were also assured that they could stop and withdraw from the interview if and when they so wished. All interviews were recorded with permission, and additional hand-written notes supported the recordings if necessary. Each interview lasted for approximately an hour – this was aligned with average interview times mentioned in other similar studies (Flint & Golicic, 2009; Flores, 2018; Grabs et al., 2016; Hughey et al., 2005; Kennedy et al., 2017; Sautier et al., 2018; Wongprawmas et al., 2015).

Dey (2003) suggests that qualitative data needs to be categorized for effective organization to help with analysis. Thus, the interview transcripts were read several times, and themes relevant to each of the two research questions were highlighted as they emerged from the readings. The use of computer software like NVivo is encouraged when conducting purely qualitative research with large amounts of data (Creswell & Creswell, 2018; Dey, 2003; Secretario, 2017). However, according to Denscombe (2010), elaborate transcription and coding is only required if the researcher wants to find the underlying meanings or implications in the data – in other cases, illustrative quotes can be used to support emerging themes, especially those of a descriptive nature of lived experiences (Seidel-Sterzik, 2019). This study was intended for scoping purposes in order to better understand the avocado sector's perceptions about sustainability initiatives (in particular potential enablers and barriers to a sector-wide VSS) and provide background context for the New Zealand avocado sector case study. Therefore, the interview data was not coded extensively – instead an overarching thematic analysis was conducted to gain insights into industry perspectives.

2.4 Qualitative study on New Zealand avocado sector stakeholder perceptions: results

2.4.1 Current initiatives

New Zealand avocado growers are generally proactive and motivated about voluntary environmental sustainability initiatives

With respect to voluntary environmental initiatives, growers were generally more proactive than downstream stakeholders. There were also many commonalities in the kinds of voluntary initiatives they had employed on their orchards. For example, many growers chose to fertilise manually instead of the indiscriminate bulk spreading method, despite the former being much more time consuming. They cited '*reduction in potential leachates*' and '*ability to understand individual tree requirements better*' as their reasons for doing so. Most of the growers used a mix of conventional and organic fertilizers like natural seaweed sprays, and many of them favoured a more organic approach to fertilizing than using only commercial and conventional fertilisers. All growers considered sustainable water use to be significant in the environmental sustainability category – they were vocal about the increasing stress on aquifers and waterways. Several growers who depend on rainfall had installed tanks in their orchards to harvest rainwater off the roof of buildings on the orchard. Some also used tensiometers to monitor their water usage, and they didn't irrigate until the tensiometer readings showed that irrigation was required. With respect to waste management, all growers chipped their tree prunings and then applied them as mulch to the base of the trees, thus directing them away from landfill. Many growers engaged in planting native trees and bushes like flax and kauri along water bodies in or near their orchards, to stop leachates in run-off from entering the water bodies. Overall, growers were happy about native birdlife increasing in these planted areas. Other initiatives included the use of a smaller mower which used less fuel, installing beehives in the orchard to increase bee populations, and using recycled gypsum from construction material for soil aeration instead of freshly mined gypsum.

Strongest drivers for voluntary environmental initiatives are commercial factors, land stewardship, and care for the environment

Based on all interviewee responses, five main drivers/motivations for implementing environmental initiatives were identified (in order of importance): 1) commercial drivers/profitability/export requirements; 2) stewardship/longevity/responsibility to future generations; 3) care for the environment/love for nature; 4) recognition/success/drive to be the best; and 5) health value; **Commercial drivers** included price premiums, profits, entry to new markets, maintenance of existing markets, and reputational advantages that translate to economic benefits. They were the most significant driver in adoption of sustainable practices:

"We implement them because they make good business sense. If it wasn't profitable we wouldn't do it."

Next came **stewardship**, which entailed a responsibility to the land and other natural resources and associated responsibility to future generations. One grower's sentiment echoed the others' when she said:

"Probably our main drivers are our responsibility for our future generations. Our responsibility as horticulturists towards our land. I believe that we are the guardians of this land. This land is only for us to guard and my upbringing, my inner person is respecting the land. I think of the land as a woman and you draw what she can bear. You don't ruin that person, you respect her and take only what the land can bear. It's not just about making money off every piece of dirt. We need to be humans and take what the land gives us. In saying all of that, we're also here to make money. There's economic as well as personal motivation."

As a point of interest, one grower mentioned that younger growers (although few in number) approach orcharding with a balanced perspective with respect to profitability and sustainability. When asked about what drives younger growers/orchard managers more – commercial success or the stewardship mentality – he answered, *"Probably a bit of both to be honest. Yes, they want*

to be commercially driven as do I, but they are open to looking outside the box and saying how else can we do that so that I can still be here in 40 years' time growing my avocados."

Third, **care for the environment** included a general awareness and sensitivity to the environmental challenges posed by agri-food systems and the need to embrace more sustainable practices:

"We don't like to see waste. We love birdlife, we love sustainability, we're not gospel-type people who say 'you must you must you must' – it's just what we do. We're not evangelists or anything – we just do what we feel we can do to contribute."

"My main motivation I suppose is all about doing the job well and looking after the environment. That's what it all boils down to."

The motivation for **recognition** involved becoming acknowledged in the industry for adoption of established best practices and going further than that via voluntary efforts:

"Our driver to engage in Global Gap with our growers is to be the best."

"We want to be environmentally oriented and we want to be recognised for being environmentally friendly."

Health considerations were the least important (mentioned only a couple of times) and mainly revolved around the impact of intensive agricultural practices on soil and water health and as a consequence, human health impacts.

Perceived benefits outweigh the challenges

Overall, the respondents believed that there are economic as well as environmental benefits to the voluntary initiatives, and the general consensus was that there were no real challenges to implementing these initiatives. In fact, even if there were, the benefits outweighed them. For example, one grower said that hand fertilizing his trees cut down his fertilizer usage by nearly 50%, which directly translated to a cost saving for him. This was a benefit though he had to put

in the effort to hand fertilise. Plus, it was beneficial to the environment in terms of reduced leachates to waterways. Similarly using recycled gypsum was more economical as well as environmentally sustainable being redirected from landfill, and therefore a benefit. There are also organisational benefits. For example, a packhouse interviewee said, *“Leadership benefits [occur] – attracting forward thinking growers and there’s a huge benefit in knowing that your business is sustainable. We can attract the right staff. When growers are looking for a place to pack and weighing up the benefits, they’re more likely to go with an organization that has a small environmental footprint.”*

Influence of previous initiatives: ‘Avogreen’ extensively implemented and widely lauded by stakeholders

The New Zealand avocado sector’s pesticide use is universally governed by the Avogreen programme run by industry association New Zealand Avocado. This is principally a monitoring programme, where avocado trees are regularly monitored for pest presence by a certified Avogreen monitor. Pest pressures change seasonally, and monitoring windows also change accordingly. If pests are observed above a particular threshold level, then the trees are sprayed with pesticides targeting only the pests that have been found. Thus, Avogreen is operated on the ‘monitor before spraying’ premise. This method of spraying is a significant change from pre-Avogreen years, when generic pesticides were sprayed as per a spray schedule decided at the beginning of the year, irrespective of actual pest pressures. The Avogreen programme has now become an intrinsic part of the avocado sector in New Zealand and all growers are required to be Avogreen-certified if they intend to export their produce. Thus, it has become ‘de facto’ mandatory for growers to be Avogreen compliant.

The pilot study showed an overwhelmingly positive response to the scheme and its perceived environmental and economic benefits. A majority of the interviewees did not find the Avogreen programme to be inhibiting, cost- or time-wise. Some said that not having to spray was actually a cost-saver, despite the small fee required for an external monitor or the one-time certification

fee. The general opinion was that Avogreen had transformed pest management in the New Zealand avocado sector and made it a far more environmentally sustainable sector than it used to be pre-Avogreen:

“Avogreen costs us money, but it’s a requirement and we’re prepared to pay for it. We’ve gone from using ten sprays a year to barely getting four on. So, there’s a significant cost-saving.”

One orchard manager emphasized the importance of Avogreen to the sector saying that *“it’s the only real biggest step the industry has made in terms of environmental changes.”* Another said, *“Avogreen is fantastic. Avogreen has helped me get not organic, but halfway there. Before, when I arrived on the orchard, people said I’m going to start the season and I’m going to use a general spray and kill everything. That’s what people did. Clean the whole orchard up all in one go. People didn’t realise that in doing that you killed all the lady birds and other beneficials. It was easier and acceptable in those days. This is only around 6 years ago. Now I think it’s great that we have to have a look first and I only put on a fraction of the sprays that was going on when I first bought this place. So you measure and identify your pests and then target those pests with specialist sprays and they’re not broadband ones that kill everything, only certain ones. It’s got to be better for me putting them on, better for the environment, better for the export. Avogreen – no I don’t think any other country does it – Avogreen has been brilliant.”*

A few drawbacks were noted, including unavailability of contractors when needed and shortcomings in the Avogreen programme itself:

“To be honest, I find that it can be improved on. I find it can be a lot more astute on what chemicals we spray and how we use them. At the moment, we’re just monitoring for the pests, making sure we don’t spray before the threshold or making sure you’ve got a window to spray in. What’s not really monitored is the choices of spray people use, building up resistance to those sprays, understanding the impact on the beneficial insects etc.”

Global G.A.P. considered to have little focus on environment, no performance-based metrics, and to be time- and cost-intensive

Global G.A.P. is a worldwide standard that assures Good Agricultural Practices (G.A.P.), mostly focused on on-orchard/on-farm practices. This G.A.P. certification for fruits and vegetables comprises a checklist audit that covers food safety and traceability, environmental sustainability and worker health, safety and welfare. All avocado exporters in New Zealand require their growers to be Global G.A.P. compliant to meet the requirements of their export markets. Therefore, although not mandated by the government, Global G.A.P. has become a de facto mandatory scheme for export avocados. Five main perceived benefits of G.A.P. certification emerged from the interviews: 1) improved standing of New Zealand-grown avocados in export markets; 2) effective demonstration of traceability, food safety and to an extent, sustainability credentials; 3) market access; 4) increasing awareness of global agricultural standards among growers; and 5) some environmental benefits, especially with respect to chemical use and storage:

“Well people in other countries get to know that our products are safe. That’s I suppose one of the benefits of being able to sell in the New Zealand clean green image overseas. And it’s becoming a bigger and bigger issue all the time because you’ve got people claiming that their products are healthy and clean but they’re not.”

“It’s also sort of starting to get a little bit of awareness out there. There are some individual growers who are doing some very good things. So, it is motivating them – they are starting to think of things like what are their practices on the orchard doing to streams, to the land and air. So, it is starting to see a change here.”

One of the main drawbacks that the interviewees identified with the G.A.P. certification is that it is far more focussed on health, safety and food hygiene and safety, than on environmental sustainability. As there are a lot of recommended (rather than required) criteria related to environmental issues, interviewees felt that this made the system less stringent and ‘not very

thorough from an environmental sustainability point of view'. One grower also pointed out that even though he was proactive about certain environmentally positive measures, these were not considered in the audit because there were no criteria available for it. Most importantly, respondents noted the conspicuous lack of performance-based indicators in the audit, universally calling it a 'tick box' type of evaluation rather than one based on measurable metrics that could facilitate continuous improvement:

"No there are no quantifications. As long as you're talking about our fertilisers for example, we do. We get a soil and leaf sample every year and we get professional advice. So the Global GAP question is whether we have justified the fertiliser use, how we're doing it, etc. They don't ask us how many nitrogen units, how many potassium or calcium units are in that recommendation – which is quantitative. No. they ask us whether we do a soil or leaf sample test and so we get a suitably qualified professional to give us advice on what's needed – that's as far as the auditor goes."

Another grower echoed this sentiment: *"With fertilizers, they ask for your soil report etc., but that's as far as it goes. They're just checking that what you're doing is being recommended by a professional and you're not over-indulging the plants."*

One of the main concerns the respondents expressed was the significant time, money, and administrative resources that were required to obtain and maintain G.A.P. certification. Cost was especially seen to be problematic for the smaller orchardists who had to contend with spending the same amount of financial resources for G.A.P. certification, as the larger orchards:

"If you're a small grower or a big grower, you still have to do the same sort of compliance. You don't get compliance for a half hectare and therefore for 12 hectares its 24 times as big. So, smaller growers in particular find the compliance to be very expensive."

Even packhouses found the resources required to be invested in preparing for and getting audited to ensure they adhere to the G.A.P. traceability and Chain-of-Custody requirements and source from G.A.P. certified growers were significant:

“Global GAP is like all compliance – it always keeps growing. And its cost always tends to escalate. For example, we have a whole section now with 4-5 people in the compliance group who do nothing but compliance. It’s just a continuous escalation of auditing and checking and paperwork etc.”

Despite the concerns regarding these resource investments, most interviewees took a practical, matter-of-fact approach to G.A.P. certification, saying that they bear the extra cost and put in the time and efforts necessary because it is de facto mandatory for exports and therefore a business requirement. However, many interviewees emphasized that if there was no retailer pressure to be G.A.P. certified and if it was a purely voluntary scheme, they would not engage in it and there would be little or no uptake from the industry, given the time, cost and other overheads in compliance measures and audits.

2.4.2 Potential VSS-based environmental certification scheme

Main potential barriers are time, cost, added administrative processes, lack of demonstrated environmental impacts, and lack of consumer demand

Given the assumption that a future environmental certification scheme would be voluntary, the principal barrier to developing and implementing such a scheme is a lack of uptake by growers, and to a degree packhouses and exporters. The main reasons cited are the increased time, cost and general administrative processes associated with compliance efforts, and the fact that most people are averse to the efforts and resources required for compliance. Cost would be less of an obstacle for a larger orchard; however, for smaller orchards, it would be an inhibiting factor:

“Many orchardists work off-orchard. So, they have professional careers and they do this when they can and therefore there’s a time factor involved. Time and extra costs would be an obstacle.”

“It’s the paperwork and compliance side of it that would be the challenge. I don’t think many people would uptake this. A lot of growers are getting cheesed off with all the compliance. There

are a number of growers that we have spoken to and they are struggling with the compliance to everything now and you implemented something else, I could see these antennae just go Bing!"

Intangible and vague 'possible' benefits could also hinder uptake:

"One of the main barriers would be buy in from landowners and growers. They need to know what the value is and sometimes when you're talking environmental sustainability, the benefits are very intangible."

Lack of research into the inputs and outputs in the avocado production chain, and the resulting conspicuous absence of data regarding the environmental impacts of on- and off-orchard processes were viewed as significant obstacles to the development, implementation and uptake of an environmental certification scheme. Some respondents said that they were more environmentally proactive than others, but due to the intangibility of environmental benefits as mentioned above, there was no perceived benefit of their efforts since the environmental impacts of their actions could not be measured:

"One of the huge disadvantages of the New Zealand avocado sector is there's very little research going on, very little scientific background. Nobody would have any idea whatsoever about what the nitrogen loss from an avocado orchard would be – no one's measured it and there's no data and that's got to change but I don't know how we're going to change it."

Lack of such important data also results in ambiguities about environmental burden shifting which leaves growers confused about which actions to take so that their on-orchard practices are optimised from a sustainability point of view:

"It's pretty hard to make an environmental judgement. For example, cutting the grass – we didn't think of it as important because we view that as purely aesthetic and cutting grass involves using fossil fuels. But we know that if we leave the grass longer, we have problems with moss which brings more leaf roller, which then requires more pesticides. But how do we know which one has

lesser environmental impact - using lesser fossil fuels or less pesticides. Do they cancel each other out? How do you measure the burden shifting?"

Another obstacle to a certification scheme was perceived as a lack of demand from the consumer (retailer as well as end customer) end. Retailers in importing countries often have their own requirements which the exporter must meet, in order to supply them with the product. If retailers in importing countries do not feel the need for a comprehensive certification scheme, then growers, packers and exporters in New Zealand won't be driven to engage in it. Similarly, if end consumers in export markets are not aware of the certification scheme and its environmental and economic benefits, they wouldn't demand a scheme like this, and they would certainly not be willing to pay a premium for it. The lack of end consumer awareness also ties in with what interviewees called 'consumer confusion' and this could be a significant barrier to consumers choosing to purchase certified environmentally sustainable avocados:

"I think it makes it tricky though because then you'd have organic fruit and then environmentally sustainable fruit. There'll be a lot of confusion because the consumers will say well what's the difference here? I think that would be the main issue with putting another certification type thing out there. Also, with avocados, as a consumer myself, before I even came here I was like avocados are so good for you, full of vitamins and stuff. So you kind of don't even think that they will have issues when they grow them. You don't even think they spray all these things on them, you just think oh it's a tree and it's like going to a forest and picking avocados you know. That's the mindset. So if someone comes and tells you ok buy these avocados because they're environmentally friendly then you go like oh what's wrong with the other normal ones?"

Main potential enabler is perceived commercial benefits

Interviewees generally agreed that a potential new VSS-based environmental certification scheme might lead to environmental benefits but didn't go into specific details about what kind of environmental benefits might be expected. On the other hand, they were more vocal about the possible economic/financial/business benefits. According to the respondents, a scheme like this

could differentiate the New Zealand avocado in export markets, which in turn could boost marketability of the fruit due to demonstrated environmental credentials. A few interviewees even thought that this could potentially facilitate price premiums and increased profit margins:

“Well, arguably yes, we could get a price premium”. I don’t see why not. Especially going forward, I mean our generation is pretty pro everything in terms of looking after the earth, so if you could supply another box that has been ticked to show that this grower by your standards is environmentally sustainable, then why not?”

“In theory it’s going to slow down the impact of environmental issues. If it’s valuable, price premiums, image enhancements, marketability should all come through. It will be reflected in the marketplace.”

Others were sceptical about certification translating into actual further price premiums, because many of the export markets, especially those in Asia, are not that interested in environmentally sustainably grown fruit. Their principal emphasis remains on strict biosecurity measures, and they demand good size fruit of high quality and nutritional value, rather than focusing on the sustainability aspects.

Respondents mostly agreed that a life cycle-based certification scheme could help New Zealand’s avocado sector maintain and even enhance its image in export markets. They pointed out that New Zealand can’t keep falling back on the current ‘clean green’ image that it depends on to export its products – the industry needs to reinforce the country’s image by telling the New Zealand sustainability story:

“I believe that as a country we have to start telling our sustainability story. I think that we as a country need to start driving that point of difference and we need to start waking up and doing something about it.”

“It’ll create a place for New Zealand avocados in the current market. Currently everyone’s exporting their avocados everywhere in the world. So, we have to go back to differentiating and how you differentiate is you tell them it comes from New Zealand and why is New Zealand different

– because we do it this way and this is part of the New Zealand story. Demonstrating that clean green image is important. I think we’ve got it, but the hardest thing is to keep that image. To keep the image, we have to prove we’re doing it.”

So, although the scheme might not result in price premiums, telling the sustainability story could potentially make it easier to sell the fruit into a constantly changing and increasingly competitive export market. Avogreen was cited as an example of a scheme that began as a marketing strategy to obtain price premiums but resulted in ease of sale more than profit margins.

Other potential enablers include tangible demonstration of potential economic benefits and environmental impacts, reduced administrative processes, information sharing, and streamlined export structure

The most important enabler of the scheme would be to get sufficient buy-in from growers. To this end, interviewees emphasized the need to demonstrate to growers the tangible values of the scheme, particularly the economic benefits. This would need to include differentiation of the fruit in the export markets and resulting price premiums, any cost-savings that may result from the scheme, and evidence of consumer/retailer demand for those sustainability credentials.

Many respondents agreed that economic benefits would go hand in hand with the environmental value of a potential certification scheme, and this needs to be demonstrated clearly and quantifiably to stakeholders (particularly growers). They voiced the need for research in this area to demonstrate the environmental impacts of the sector and what the certification scheme does to reduce those impacts, to get growers and post-harvest operators/exporters interested in the scheme:

“We need to be able to measure what impact we’re having now. When people can see the benefits of it, then everyone will buy into it. Because unless you can see any benefits, there’s no point in doing it is there?”

“Quantification of environmental impacts and demonstrating that to growers would be the core of any strategy, absolutely, that would sell it. That’s where a lot of the cynicism is – of what value is it to us. So, you can say here’s the value chain, here’s what’s happening now and by taking these steps this is what the outcome will be.”

“Well quantified data is showing people that its having an effect. But you need to go a step further and say that by doing this you can reduce that effect or change that effect. But we first need to know what impact we’re having.”

Some of the interviewees particularly spoke of the need for such studies to be applicable to the entire value chain (avocado growing, harvesting, packaging, transport, shipping and consumption):

“We are just thinking about the orchard impacts. But then there’s transport and packaging, what are the trays made from etc. and then there’s the transport overseas, shipping or air freight...”

To this end, interviewees emphasized the need for further in-depth research to demonstrate to growers the environmental impacts of the sector and what the certification scheme could do to reduce those impacts, to get growers and post-harvest operators/exporters interested in the scheme.

Many interviewees said that the scheme should allow for easy transition to lower impact processes, so that stakeholders (especially growers) aren’t put off by the requirement for drastic changes. Many of the interviewees also said that people prefer to not have to waste more time, energy and money in additional compliance processes (as mentioned earlier). Thus, having a standalone certification scheme separate from Global G.A.P. would be counterproductive as there would be no uptake by growers, packers or exporters. Combining the scheme with Global G.A.P. requirements would make the process easier and get it the traction needed for uptake; most of the compliance requirements for both standards (or additional criteria, if incorporated into NZGAP) could then be cross-referenced and finished in the same audit. Also, fruit certified under a standalone scheme would have to be picked and packaged separately, and there would

have to be large quantities of fruit certified to such a scheme to justify the costs involved in separate harvesting and packaging processes:

“It would have to be done under the umbrella of NZGAP or Global GAP. Because the fruit is pooled in the packhouse, the people that would do it solo as a standalone audit, wouldn’t see a benefit because it would be pooled amongst other fruit. Grower a and grower b – one could be compliant and have the certification, but his fruit would be pooled with other normal fruit and exported together so it wouldn’t be able to have that label showing this certification. Alternately, it would have to be packed separately as standalone in the packhouse. If you have the volume, then it’s feasible. But you need the volume. So, there would need to be adequate grower buy-in for a certification scheme like that. It would have to make financial sense for the packhouse to have the fruit harvested separately, packed separately, different pack time all that sort of thing.”

Also, any novel New Zealand-based environmental certification scheme would need to be recognized in the importing country and would therefore need to demonstrate a high level of credibility on par with international certification schemes recognised in export markets. This complemented the opinion that including the new scheme under the auspices of Global G.A.P. would provide it with the required credibility. In addition, if the new standards were based on quantified measures of environmental impacts, that would lend it further credibility and by consequence, legitimacy.

Implementation should involve a pilot sector project which is subsequently expanded to the entire horticulture industry, and that enables telling a single New Zealand horticulture sustainability story

Most interviewees were in favour of developing and implementing a scheme that spanned the entire horticultural industry of New Zealand. This could be started as an umbrella scheme from the get-go (either just one overarching scheme or sub-schemes catering to the specific requirements of each sector), or as a pilot study in one sector and then replicated in other horticultural sectors. Interviewees said that the single overarching umbrella scheme would be

easier to implement in the long run, from a marketing point of view as well as considering the long-term sustainability of the programme:

“The whole industry should be involved because you don’t want a fragmented approach to this. The bigger the industry that’s contributing, the bigger the result. The more value it has. The more of an impact. If it’s just within avocados, it won’t be big enough to sustain itself. A single sector wouldn’t support a programme like that. There wouldn’t be an economic benefit coming from it.”

In the case of an umbrella scheme with sub-schemes under it, it would be vital for the certification system to be simple enough to be easily applied across the sectors, to make it easier for growers with multi-crop orchards. However, some respondents also said that the New Zealand horticultural industry is too big to implement a single overarching scheme. They suggested that it would be better to focus on one sector (preferably avocados) for a pilot certification scheme, which when successfully implemented can then be adapted to the other sectors in the industry. It was also suggested that the avocado sector is ‘*in tune with the environmentally conscious grower*’, making it a good candidate for a pilot certification scheme.

All interviewees were universally of the opinion that any new environmental certification scheme must essentially be a multi-stakeholder initiative (MSI) with representation from all horizontal and vertical actors along all the stages in the value chain, i.e. along the life cycle of the product:

“I think you’re going to want to have to have everyone in the loop on board with the scheme. If you’ve got the growers that are all keen and wanting to do it, but you don’t have the demand or avenues, then you can grow all the compliant fruit and have your certification, but the market may not be interest or there may be limited markets for it. So, everyone has to be on board otherwise somewhere down the line it’ll collapse.”

Opinions were divided about the stakeholder collaborations that would most effectively drive the programme to success. Some interviewees suggested that industry organisations like New Zealand Avocado should spearhead a potential certification scheme, mainly because they have

the funds (levies and government assistance) that would be required to support a scheme like this. Others said that the scheme should be an equal collaborative effort between all stakeholders (growers, packers, exporters, government, certification bodies and others), but heavily supported by New Zealand Avocado. In terms of developing the plan, one idea was that a small working group led by NZ Avocado could come together on a pilot VSS programme implementation project before seeking representation from different parts of the value chain. Still others said that the top industry body Horticulture New Zealand should be the one driving the scheme. Another interviewee stated that while the scheme should be an MSI, its implementation should rest with the exporters, specifically with AVOCO, since it controls 60% of the export production. Given AVOCO's influence in the New Zealand avocado sector, the interviewee's opinion was that whatever AVOCO adopted would be adopted by their growers.

In summary, the following findings emerged from the study:

1) Current sustainability initiatives

- New Zealand avocado growers are generally proactive and motivated about voluntary environmental sustainability initiatives
- Strongest drivers for voluntary environmental initiatives are commercial factors, land stewardship, and care for the environment
- Perceived benefits outweigh the challenges
- Influence of previous initiatives: 'Avogreen' extensively implemented and widely lauded by stakeholders
- Global G.A.P. considered to have little focus on environment, no performance-based metrics, and to be time- and cost-intensive

2) Potential VSS-based scheme

- Main potential barriers are time, cost, added administrative processes, lack of demonstrated environmental impacts, and lack of consumer demand
- Main potential enabler is perceived commercial benefits

- Other potential enablers include tangible demonstration of potential economic benefits and environmental impacts, reduced administrative processes, information sharing, and streamlined export structure
- Implementation should involve a pilot sector project which is subsequently expanded to the entire horticulture industry, and that enables telling a single New Zealand horticulture sustainability story

2.5 Qualitative study on New Zealand avocado sector stakeholder perceptions: discussion

The pro-environmental ethos of the horticultural and viticultural sectors in New Zealand has been documented in previous studies (Baird et al., 2018; De Silva & Forbes, 2016; Dodds et al., 2013; Gabzdylova et al., 2009). For example, De Silva and Forbes (2016) noted that most horticultural growers in New Zealand implement sustainability practices voluntarily. These practices mainly cover integrated pest management, waste management, soil protection, water conservation, habitat/wildlife protection, and energy efficiency. This scoping study showed the New Zealand avocado sector (as a subset of the wider horticultural industry) also has the same ethos. The stakeholders interviewed were generally forward-thinking and proactive in their approaches to implementing a range of voluntary sustainability initiatives. Stakeholders, especially the growers, are driven to implement these practices because of perceived benefits not just in terms of profitability and meeting regulatory requirements, but environmental benefits as well. In fact, land stewardship for future generations, and concerns about the environment are significant motivations for growers to adopt sustainability initiatives voluntarily, similar to those observed in the New Zealand wine sector (Baird et al., 2018; Dodds et al., 2013). They are willing to invest time, effort and resources to participate in such activities and programmes, because they believe the benefits of doing so outweigh the challenges. Such strong pro-environmental motivations make the avocado sector well-suited for a sustainability initiative like a VSS-based certification scheme.

Of the two *de facto* mandatory programmes employed in the New Zealand avocado sector, Avogreen has been universally accepted and commended as being a transformative initiative that has made the New Zealand avocado sector more aware of the prudent use of agrichemicals. This has also translated into financial savings in addition to environmental benefits. This is not entirely surprising, since Integrated Pest Management (IPM) principles, on which Avogreen is based, are an important component of sustainable farm management in most horticultural sectors worldwide. In New Zealand, the SWNZ programme began as a pilot project to implement IPM practices in the wine sector (Sautier et al., 2018), and other sectors like kiwifruit, apples, and vegetables in New Zealand have had their own established versions of IPM standards integrated into their sustainability programmes (A Lighter Touch, 2025; New Zealand Apples and Pears, 2024b; Zespri, 2025). Since the Avogreen programme includes disciplined data entry into growers' spray diaries, the detailed information on pesticide use on individual orchards is now available on a centralised platform, making it an organised and up-to-date data source for pesticide use. Moreover, interviewees did not find the Avogreen programme to be time- or cost-inhibiting. Thus, the Avogreen programme and Spray Diary platform could be a useful component in the development and implementation of a potential VSS-based scheme in the avocado sector.

Unlike Avogreen, stakeholders view the Global G.A.P. certification scheme (the other *de facto* mandatory requirement for avocado exports) as something they need to do as a business requirement rather than something they would do if it was entirely voluntary. The main reasons cited for this are the large time, cost and administrative commitments associated with Global G.A.P. audits. Any additional financial and other resource investments required for a new VSS were considered highly undesirable. As noted in Section 2.2, the financial investment required for audits, certification processes, and upgrading of practices to meet VSS requirements is universally considered a barrier to VSS adoption across developed and undeveloped countries. The issue with time constraints and administrative burden noted by interviewees was also consistent with a previous study on the uptake of EurepGAP (the predecessor to Global G.A.P.)

among New Zealand kiwifruit growers (Rosin et al., 2008). The authors had noted that orchardists can get frustrated with the prospect of large amounts of additional paperwork associated with VSS compliance. This was exacerbated when the VSS was perceived as not adding much value to the standards that were already in place at the time. The latter is another determinant of VSS adoption noted in the literature review: the perception of little or no value addition from the VSS, caused/compounded by the lack of clarity about the tangible benefits of VSS adoption (Baird et al., 2018; Hannus & Sauer, 2021; Lees, 2020; Nyblom, 2020; Rosin et al., 2008).

While Global G.A.P. certification has opened up new markets for producers by standardising agricultural best practices worldwide (Bešić et al., 2015), it continues to focus more on food safety and hygiene rather than environmental sustainability (Annor et al., 2023; Masood, 2015). The interviewees also noted the weak representation of environmental sustainability in the standard criteria as one of the main drawbacks of the scheme. Also, as Kalfagianni and Fuchs (2012) and some interviewees point out, many of the environment-related points in the GAP scheme are merely ‘recommendations’ rather than requirements. This means the certification can still be awarded even if the organisation does not comply with these environmental recommendations. Also, Global G.A.P. is a classic checklist-type ‘pass/fail’ standard with predominantly practice-based criteria. Interviewees were quick to point out the conspicuous absence of measure performance metrics in the standard¹⁹. Despite these drawbacks, Global G.A.P. is perceived to have a high standing as a sustainability VSS in international markets and is often an institutional requirement for exporting fresh produce. Thus, interviewed stakeholders consistently stated that if new environmental criteria are to be introduced into the sector, plugging them into an existing and globally accepted scheme like Global G.A.P. instead of having a standalone scheme would definitely encourage their wider sectoral uptake. However, Global

¹⁹ The most recent iterations of the standard have expanded the scope of environmental criteria, with ongoing plans to make it even more comprehensive, including the addition of performance metrics by 2025 (Global G.A.P., 2024a).

G.A.P. does not permit national level metrics to be included in the standard. One way to address this challenge is to incorporate (as a starting point) the new criteria into NZGAP – the national level G.A.P. scheme benchmarked to Global G.A.P.²⁰. While this would not immediately influence export requirements (Global G.A.P. is expected to continue to be a requirement, not NZGAP), it could help the sector begin the process of moving towards uptake of more performance metrics.

Given the significance interviewees placed on time, cost, and administrative burdens as a perceived drawback of the Global G.A.P. scheme, it was not surprising that they also stated these factors as potential barriers to a new VSS in the sector. Similarly, the ambiguity around tangible impacts of the scheme (environmental, social, financial) was identified as an important barrier to the uptake of a new VSS; this has been noted in literature as well (Hannus & Sauer, 2021; Lees, 2020). Moreover, interviewees observed that there was a lack of knowledge/understanding of the sector's current environmental profile in terms of quantitative, scientific data – and this was perceived to be a barrier to uptake of a new VSS. Thus, quantitative data about environmental performance of individual stakeholders and the sector as a whole could be a driver for VSS uptake. This was observed in the case of SWNZ when it was being developed as a new sector-wide VSS: there was a strong focus on performance metrics, so that growers could understand their impacts quantitatively, and improve over time (Sautier et al., 2018).

Another barrier to the uptake of a new sector-wide VSS is lack of retailer/consumer demand for the scheme. Major retailers (e.g. Walmart, Tesco, Marks and Spencer, Sainsburys, and Woolworths) are known to be drivers of sustainability practices and standards – they implement these standards in their supply chains to encourage best practice and build consumer trust

²⁰ The Global G.A.P. system is unique in that national level G.A.P.s with their own certification rules and GAP requirements can be benchmarked to the Global G.A.P. standards (Global G.A.P., 2024b). Several countries, including Chile, Mexico, Kenya, Malaysia, Thailand, and New Zealand have national GAP standards benchmarked to Global G.A.P. (Nabeshima et al., 2015; NZGAP, 2023; Valk & Roest, 2009).

(Chkanikova & Sroufe, 2021; Duffy & Fearne, 2009; Giacomarra et al., 2021; Thorlakson et al., 2018). Indeed, Global G.A.P. certification itself began as a retailer-led initiative in the UK and Europe and has now experienced widespread diffusion and high adoption intensity, expanding into one of the largest multi-stakeholder voluntary standards for sustainable agriculture (Mohammed & Zheng, 2017). Thus, successful VSS adoption is likely to be dependent on downstream retail demands.

The main driver for stakeholders to adopt a new VSS was business advantage, i.e. commercial factors like product differentiation in export markets leading to market access and possible profitability due to price premiums. However, opinions were divided about the actual potential of obtaining such premiums; some interviewees believed such premiums were a possible consequence of demonstrating sustainability credentials via a VSS, and others did not expect that the VSS would translate into actual profitability. However, most interviewees stated market access/retention as a more likely driver for uptake. Such differing opinions were noted in literature as well, with stakeholders more confident about the potential of the VSS to differentiate their products enough to gain entry into a new market or continue in existing markets, rather than obtaining price premiums for products with sustainability credentials (Baird et al., 2018; Gabzdylova et al., 2009; Hannus & Sauer, 2021; Lees, 2020; Sautier et al., 2018).

In the literature review, image/brand equity and reputational advantages were identified as drivers to VSS adoption in developed countries. This is especially relevant in New Zealand, where the export-oriented primary sectors use the country's clean, green image as a point of differentiation (Flint & Golcic, 2009; Foote et al., 2015; Hughey et al., 2005; Sautier et al., 2018; Stenton-Dozey et al., 2021). However, New Zealand's reputation as a clean, green country has been questioned in recent years as concerns are raised about a disconnect between this image and New Zealand's environmental realities, especially related to climate change, and marine/freshwater pollution (Kaefer, 2014; Ulrich & Handley, 2020). Thus, developing and

maintaining a credible New Zealand sustainability brand and telling the New Zealand sustainability story continues to be important for the primary sector (MPI, 2023). Brand enhancement was identified as a driver for VSS uptake in the New Zealand avocado sector; interviewees acknowledged that depending on New Zealand's historic clean, green image without making the efforts to keep supporting that with demonstrable credentials would be unproductive in future. They emphasized the need to 'tell the New Zealand sustainability story'. Other studies have also touched on this point about the need to enhance New Zealand's positive image by telling its sustainability story (Flint & Golobic, 2009; Lees, 2020; Sautier et al., 2018). For example, Lees (2020) uses Ireland's Origin Green as a case study for a national agri-food sustainability brand and emphasizes the need for (and potential of) a similar brand for New Zealand, to effectively demonstrate New Zealand's agri-food sustainability credentials, not as splintered industry sectors, but a united front representing the country as a brand. As Bardsley et al. (2020) state in their report on the future of food and the primary sector in New Zealand, *'New Zealand needs to develop and market a national accreditation scheme that reflects the nature of our future food production and is evidence-based. We also need to consider how to better link our brand to the unique cultural identity of Aotearoa and promote our aspirational social, cultural and environmental values.'* Several interviewees acknowledged that an existing or new scheme with science-based performance metrics relevant to the avocado sector would be perceived as reliable and transparent, and augment New Zealand's clean, green reputation in export markets. Since there has been little or no research on the environmental impacts of the New Zealand avocado sector, quantifying the sector's environmental performance would help stakeholders understand their impacts, set benchmarks and facilitate continuous improvement via for example VSS-based schemes. Most respondents favoured taking a life cycle perspective and including the whole value chain in this process. Thus, the development of LCA-based benchmarks and indicators for the avocado sector will be central to any future continuous improvement programme or VSS.

Lastly, interviewees were universally of the opinion that a new VSS for the avocado sector should be a multi-stakeholder initiative and involve actors from all stages of the value chain. Opinions were divided regarding who should drive the development and implementation of the scheme. However, several interviewees agreed that the sustainability message as part of the New Zealand sustainability story should not be limited to the avocado sector; rather, they advocated that the VSS be an umbrella scheme covering the entire horticultural industry. This reflects the brand image developed by other multi-sector national level schemes like Origin Green and Red Tractor (Deconinck & Hobeika, 2023; Lees, 2021). However, stakeholders also acknowledged that this would not be feasible all at once. It would need to be trialled within one sector first (for example, avocados), and then extended to include other horticultural sectors, and potentially other agri-food sectors as well. Thus, given the strong industry structure, the sustainably forward-thinking stakeholders, and the need for LCA-based performance metrics in the sector as mentioned above the New Zealand avocado sector could potentially be the pilot sector to trial the development and implementation of the proposed life cycle-based VSS.

With respect to limitations, the study did not incorporate a full-fledged qualitative approach with in-depth coding as it was a basic scoping study to support the use of the New Zealand avocado sector as a case study for the LCA research (Chapters 3 and 4). A future study could build on this one and incorporate detailed coding and analysis. Second, the study did not include certain stakeholders like nursery operators, Global G.A.P. certifiers, Avogreen monitors, government officials, retailers, and end-consumers. Again, this was because it was a scoping study meant to provide an overview of insights into stakeholder perceptions – a future study would benefit from the inclusion of additional stakeholder types.

2.6 Conclusion

The New Zealand avocado sector is progressive, with a strong sectoral association and clear sustainability goals. The aim of the current study was to engage with stakeholders in the avocado sector, and gain insights about their perceptions of sustainability, and current/future

VSS, in order to better understand the potential for the development of a VSS for the sector, particularly one which is based on life cycle considerations. The study reported in this chapter found that the New Zealand avocado sector is proactive about the uptake of voluntary sustainability practices and values environmental considerations and land stewardship (along with commercial benefits) when implementing these practices. Stakeholders were positive about the transformational value of the Avogreen programme to the sector. However, they were less enthusiastic about Global G.A.P., which they believed to be less than optimal with respect to the environmental sustainability criteria; they considered it more of a business requirement for exports rather than something that adds actual value otherwise. They cited commercial benefits (profitability, market access, personal and national brand enhancement) as the main drivers to the uptake of a new scheme, while time, cost, and administrative burdens were the main perceived barriers. The lack of information about tangible economic and environmental benefits was considered another potential barrier and stakeholders envisaged increased uptake of a new scheme if there was more data about consumer demand, potential price premiums, and scientifically determined quantitative environmental impacts. They agreed that it would be beneficial to take a life cycle perspective when developing the scheme and not to expect only growers to take responsibility for environmental improvement. They also believed that a future scheme should include multiple horizontal and vertical actors along the value chain, be trialled in the avocado sector, and then expanded to become an umbrella scheme for the entire horticultural industry to tell the New Zealand sustainability story from a unified front.

Thus, the main finding of the study was that the New Zealand avocado sector is well-placed as a case study for the development of LCA-based performance metrics and indicators for use in a sector-wide VSS. This serves as a foundation and justification for the LCA studies which follow in the next chapters. The study also provides standalone value as it addresses several research gaps identified in literature:

- It is relevant to the context of a developed country

- It takes into consideration downstream actors like packers and exporters who are underrepresented in studies identified in literature
- It is an ex-ante analysis
- It evaluates the potential for a sectoral VSS based on life cycle considerations, and/or LCA-based criteria
- It contributes to literature on the adoption of sustainability practices in the avocado sector of New Zealand, which has not been studied yet.

This qualitative study provided the basis for selecting the New Zealand avocado sector as a case study for an LCA study, which is presented in Chapters 3 and 4 of this thesis.

References

- A Lighter Touch. (2025). *Programme Overview – A Lighter Touch*. <https://a-lighter-touch.co.nz/programme-overview/> (Accessed 17 February 2025)
- Annor, P. B., Kaitibie, S., & Lyne, M. C. (2023). Heterogeneous impacts of GlobalGAP adoption on net income in small-scale pineapple farming in Ghana: Does farm size matter? *Agribusiness*, 39(4), 1199-1216. <https://doi.org/10.1002/agr.21821>
- ASB Bank. (2018). *Commodities Weekly. Kiwifruit and horticulture: The fourth engine*. Available for download at: <https://www.asb.co.nz/documents/economic-research/commodities-weekly/kiwifruit-and-horticulture-the-fourth-engine.html>
- Baird, T., Hall, C., & Castka, P. (2018). New Zealand Winegrowers Attitudes and Behaviours towards Wine Tourism and Sustainable Winegrowing. *Sustainability*, 10(3), 797. <https://doi.org/10.3390/su10030797>
- Bardsley, A., Coates, B., Goldson, S., Gluckman, P., & Kaiser, M. (2020). *The future of food and the primary sector: the journey to sustainability*. Available for download at: <https://informedfutures.org/the-future-of-food-the-primary-sector/>
- Bešić, C., Bogetić, S., Čočkalo, D., & Đorđević, D. (2015). The role of GLOBAL G.A.P.: In improving competitiveness of agro-food industry. *Ekonomika Poljoprivrede*, 62(3), 583–597. <https://doi.org/10.5937/ekoPolj1503583B>
- Brandi, C., Cabani, T., Hosang, C., Schirmbeck, S., Westermann, L., & Wiese, H. (2015). Sustainability Standards for Palm Oil: Challenges for Smallholder Certification Under the RSPO. *The Journal of Environment & Development*, 24(3), 292–314. <https://doi.org/10.1177/1070496515593775>
- Chalmers, H. (2019). *Orchards replace dairy farms*. Stuff. <https://www.stuff.co.nz/business/farming/112094791/horticulture-and-forestry-replace-dairy-as-primary-sector-darlings> (Accessed 24 April 2019)
- Chelang'a, N. C., Kariuki, I. M., Obare, G. A., & Otieno, D. O. (2023). Determinants of adoption of GLOBAL G.A.P. standards: Evidence from smallholder French beans farmers in Murang'a County, Kenya. *Cogent Food & Agriculture*, 9(1), 2176949. <https://doi.org/10.1080/23311932.2023.2176949>
- Chkanikova, O., & Sroufe, R. (2021). Third-party sustainability certifications in food retailing: Certification design from a sustainable supply chain management perspective. *Journal of Cleaner Production*, 282, 124344. <https://doi.org/10.1016/j.jclepro.2020.124344>

- Coral, C., & Mithöfer, D. (2022). Contemporary narratives about asymmetries in responsibility in global agri-food value chains: The case of the Ecuadorian stakeholders in the banana value chain. *Agriculture and Human Values*, 40, 1019-1038. <https://doi.org/10.1007/s10460-022-10405-3>
- Creswell, J. W., & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. (5th ed.) SAGE Publications.
- Denscombe, M. (2010). *The Good Research Guide: For Small-Scale Social Research Projects: For small-scale social research projects*. United Kingdom: McGraw-Hill International.
- De Silva, T. A., & Forbes, S. L. (2016). Sustainability in the New Zealand horticulture industry. *Journal of Cleaner Production*, 112, 2381–2391. <https://doi.org/10.1016/j.jclepro.2015.10.078>
- de Vos, R. E., Suwarno, A., Slingerland, M., van der Meer, P. J., & Lucey, J. M. (2023). Pre-certification conditions of independent oil palm smallholders in Indonesia. Assessing prospects for RSPO certification. *Land Use Policy*, 130, 106660. <https://doi.org/10.1016/j.landusepol.2023.106660>
- Deconinck, K., & Hobeika, M. (2023). *Understanding the impact of consumer-oriented assurance schemes: A review of voluntary standards and labels for the environmental sustainability of agri-food products*. OECD. Available for download at: https://www.oecd.org/en/publications/understanding-the-impact-of-consumer-oriented-assurance-schemes_af917674-en.html
- Dey, I. (2003). *Qualitative Data Analysis: A User-Friendly Guide for Social Scientists*. Routledge. <https://doi.org/10.4324/9780203412497>
- Djokoto, J., Afrane-Arthur, A. A., & Badu-Prah, C. (2015). Adoption of Fairtrade Practices by Cocoa Producers in Eastern Ghana. *Central Inquiry* 1(1), 11–26.
- Dodds, R., Graci, S., Ko, S., & Walker, L. (2013). What drives environmental sustainability in the New Zealand wine industry? An examination of driving factors and practices. *International Journal of Wine Business Research*, 25(3), 164–184. <https://doi.org/10.1108/IJWBR-2012-0015>
- Duffy, R., & Fearne, A. (2009). Value perceptions of farm assurance in the red meat supply chain. *British Food Journal*, 111(7), 669–685. <https://doi.org/10.1108/00070700910972369>

- Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, 5(1), 1. <https://doi.org/10.11648/j.ajtas.20160501.11>
- FAO. (2005). *Modernizing National Agricultural Extension Systems: A Practical Guide for Policy-Makers of Developing Countries*. <https://www.fao.org/4/a0219e/a0219e03.htm> (Accessed 3 May 2025)
- Flint, D. J., & Golicic, S. L. (2009). Searching for competitive advantage through sustainability: A qualitative study in the New Zealand wine industry. *International Journal of Physical Distribution & Logistics Management*, 39(10), 841–860. <https://doi.org/10.1108/09600030911011441>
- Flores, S. S. (2018). What is sustainability in the wine world? A cross-country analysis of wine sustainability frameworks. *Journal of Cleaner Production*, 172, 2301–2312. <https://doi.org/10.1016/j.jclepro.2017.11.181>
- Foote, K. J., Joy, M. K., & Death, R. G. (2015). New Zealand Dairy Farming: Milking Our Environment for All Its Worth. *Environmental Management*, 56(3), 709–720. <https://doi.org/10.1007/s00267-015-0517-x>
- Fred, A., Kwame, T.A. E., Colecraft, A. D., Andivi, B. J.E., Kwadwo, A., & Addison, A. K. (2022). *Drivers of knowledge, attitude, practice, aspiration and perception of the Sustainable Agriculture Standard: Evidence from certified cocoa farmers in Ghana*. *RJOAS* 11(31), 125–140. DOI: 10.18551/rjoas.2022-11.14
- Gabzdylova, B., Raffensperger, J. F., & Castka, P. (2009). Sustainability in the New Zealand wine industry: Drivers, stakeholders and practices. *Journal of Cleaner Production*, 17(11), 992–998. <https://doi.org/10.1016/j.jclepro.2009.02.015>
- Giacomarra, M., Crescimanno, M., Vrontis, D., Miret Pastor, L., & Galati, A. (2021). The ability of fish ecolabels to promote a change in the sustainability awareness. *Marine Policy*, 123, 104292. <https://doi.org/10.1016/j.marpol.2020.104292>
- Global G.A.P. (2024a). *Environmental sustainability solution*. <https://www.globalgap.org/about/standard-setting/environmental-sustainability-solution/> (Accessed 4 October 2024)
- Global G.A.P. (2024b). *Global G.A.P. Benchmarking*. <https://www.globalgap.org/what-we-offer/benchmarking/> (Accessed 4 October 2024)

- Grabs, J., Kilian, B., Hernández, D. C., & Dietz, T. (2016). Understanding Coffee Certification Dynamics: A Spatial Analysis of Voluntary Sustainability Standard Proliferation. *International Food and Agribusiness Management Review* 19(3), 31-56.
- Hannus, V., & Sauer, J. (2021). It is not only about money—German farmers’ preferences regarding voluntary standards for farm sustainability management. *Land Use Policy*, 108, 105582. <https://doi.org/10.1016/j.landusepol.2021.105582>
- Henson, S., Masakure, O., & Cranfield, J. (2011). Do Fresh Produce Exporters in Sub-Saharan Africa Benefit from GlobalGAP Certification? *World Development*, 39(3), 375–386. <https://doi.org/10.1016/j.worlddev.2010.06.012>
- Horticulture New Zealand. (2024). *Horticulture NZ Annual Report 2023/24*. Available for download at: <https://www.hortnz.co.nz/about-us/annual-report/>
- Hughey, K. F. D., Tait, S. V., & O’Connell, M. J. (2005). Qualitative evaluation of three ‘environmental management systems’ in the New Zealand wine industry. *Journal of Cleaner Production*, 13(12), 1175–1187. <https://doi.org/10.1016/j.jclepro.2004.07.002>
- Irawan, N. C., Mahananto, Supriyadi, T., & Haryuni. (2024). What are the Major Barriers and Challenges Faced by Independent Oil Palm Smallholder Farmers in RSPO Certification? *Journal of Rural and Urban Community Studies*, 2(2), Article 2, 39-53. <https://doi.org/10.36728/jrucs.v2i2.3917>
- Johnson, A. (2022). The Roundtable on Sustainable Palm Oil (RSPO) and transnational hybrid governance in Ecuador’s palm oil industry. *World Development*, 149, 105710. <https://doi.org/10.1016/j.worlddev.2021.105710>
- Kaefer, F. (2014). *Credibility at Stake? News representations and Discursive Constructions of National Environmental Reputation and Place Brand*. Available for download at: <https://researchcommons.waikato.ac.nz/entities/publication/aad75154-0f28-4db2-a6ba-e7ff80deeb12>
- Kalfagianni, A., & Fuchs, D. (2012). The GlobalGAP. In *Business Regulation and Non-State Actors Whose standards? Whose development?* Routledge.
- Kariuki, I. M. (2014). Transition to Certification Schemes and Implications for Market Access: GlobalGAP Perspectives in Kenya. *Agricultural Sciences*, 5(12), 1100–1111. <https://doi.org/10.4236/as.2014.512120>

- Kennedy, S. F., Leimona, B., & Yi, Z.-F. (2017). Making a green rubber stamp: Emerging dynamics of natural rubber eco-certification. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 13(1), 100–115. <https://doi.org/10.1080/21513732.2016.1267664>
- Kusnezowa, D., & Vang, J. (2021). Creating Legitimacy in the ISO/CEN Standard for Sustainable and Traceable Cocoa: An Exploratory Case Study Integrating Normative and Empirical Legitimacy. *Sustainability*, 13(22), Article 22. <https://doi.org/10.3390/su132212907>
- Lees, D. N. (2020). *The Irish Origin Green Sustainability Brand An Evaluation of the Relevance for New Zealand*. Available for download at:
<https://researcharchive.lincoln.ac.nz/entities/publication/5aa2f4e9-fe59-4b76-b016-ad536d200a2d>
- Lees, N. (2021). *Ireland's Origin Green sustainability brand*.
<https://researcharchive.lincoln.ac.nz/server/api/core/bitstreams/722146f2-c9b1-4e24-8633-6db68d68b1a6/content>
- Lemeilleur, S. (2013). *Smallholder Compliance with Private Standard Certification: The Case of GlobalGAP Adoption by Mango Producers in Peru*. 16(4), 159-180.
- Lemeilleur, S., Subervie, J., Presoto, A. E., Souza Piao, R., & Saes, M. S. M. (2020). Coffee farmers' incentives to comply with sustainability standards. *Journal of Agribusiness in Developing and Emerging Economies*, 10(4), 365–383. <https://doi.org/10.1108/JADEE-04-2019-0051>
- Marshall, M. N. (1996). Sampling for qualitative research. *Family Practice*, 13(6), 522–525.
- Masood, A. (2015). *GlobalGAP Certification and International Trade Flows* [Doctoral dissertation, Georg-August-University, Göttingen]. Göttingen State and University Library ediss, <https://doi.org/10.53846/goediss-4895>
- Matt Reed, Nick Lewis, & Janet Dwyer. (2017). *The effect and impact of LEAF Marque in the delivery of more sustainable farming: A study to understand the added value to farmers*. Available for download at: <https://eprints.glos.ac.uk/4705/>
- Maven Consulting Ltd. (2024). *NZ Avocados Go Global Primary Growth Partnership Programme Evaluation*. Available for download at: <https://www.mpi.govt.nz/funding-rural-support/primary-growth-partnerships-pgps/completed-pgp-programmes/new-zealand-avocados-go-global/independent-evaluation-of-new-zealand-avocados-go-global/>
- Merfield, C., Moller, H., Manhire, J., Rosin, C., Norton, S., Carey, P., Hunt, L., Reid, J., Fairweather, J., Bengé, J., Quéllec, I. L., Campbell, H., Luccock, D., Saunders, C., MacLeod, C., Barber, A., & McCarthy, A. (2015). Are Organic Standards Sufficient to Ensure Sustainable Agriculture?

- Lessons From New Zealand's ARGOS and Sustainability Dashboard Projects. *Sustainable Agriculture Research*, 4(3), 158. <https://doi.org/10.5539/sar.v4n3p158>
- Mohammed, R., & Zheng, Y. (2017). International diffusion of food safety standards: the role of domestic certifiers and international trade. *Journal of Agricultural and Applied Economics*, 49(2), 296–322. <https://doi.org/10.1017/aae.2017.2>
- MPI. (2020). *Introducing New Zealand's primary industries. An outline of New Zealand's primary production and regulatory system for export.* <https://www.mpi.govt.nz/dmsdocument/39515/direct/>
- MPI. (2023). *The future of Aotearoa New Zealand's food sector: Exploring demand opportunities in the year 2050.* <https://www.mpi.govt.nz/dmsdocument/56350-The-Future-of-Aotearoa-New-Zealands-Food-Sector-Exploring-Global-Demand-Opportunities-in-the-Year-2050/>
- MPI. (2024). *Situation and outlook for primary industries, December 2024.* Available for download at: <https://www.mpi.govt.nz/resources-and-forms/economic-intelligence/situation-and-outlook-for-primary-industries/sopi-reports/>
- Nabeshima, K., Michida, E., Nam, V. H., & Suzuki, A. (2015). *Emergence of Asian GAPs and its relationship to Global G.A.P.* (IDE Discussion Paper No. 507). Institute for Developing Economies. Available for download at: <https://www.ide.go.jp/English/Publish/Reports/Dp/507.html>
- Nana, G. (2010). *Industrial sectors* [Web page]. Te Ara-the Encyclopedia of New Zealand; Ministry for Culture and Heritage Te Manatu Taonga. <https://teara.govt.nz/en/industrial-sectors> (Accessed 23 June 2025)
- New Zealand Apples and Pears. (2024a). *Apple & pear industry worth \$1.9 billion to New Zealand.* <https://www.applesandpears.nz/news-events/apple-pear-industry-worth-19-billion-to-new-zealand/> (Accessed 23 June 2025)
- New Zealand Apples and Pears. (2024b). *Sustainable production.* <https://www.applesandpears.nz/our-industry/sustainability/> (Accessed 23 June 2025)
- New Zealand Wine. (2023). *2023 Vintage will support strong demand for New Zealand wine.* <https://www.nzwine.com/en/media/media-releases/2023-vintage-will-support-strong-demand-for-new-zealand-wine/> (Accessed 23 June 2025)
- New Zealand Wine. (2025). *New Zealand Winegrowers Sustainability Report 2025.* <https://www.nzwine.com/media/rznjtruz/2025-nzw-sustainability-report.pdf>

- Npueng, S., Oosterveer, P., & Mol, A. P. J. (2023). Global and local sustainable certification systems: Factors influencing RSPO and Thai-GAP adoption by oil palm smallholder farmers in Thailand. *Environment, Development and Sustainability*, 25(7), 6337–6362.
<https://doi.org/10.1007/s10668-022-02306-6>
- Nyblom, A. (2020). *To certify or not to certify: A qualitative investigation into producer sentiments surrounding sustainability certifications in the Spanish wine industry*. Available for download at: <https://gupea.ub.gu.se/handle/2077/66352>
- NZ Avocado. (2023a). *NZ avocado annual report 2023*.
<https://industry.nzavocado.co.nz/download/2023-annual-report/> (Accessed 4 March 2025)
- NZ Avocado. (2023b). *Sustainability*. New Zealand Avocado.
<https://industry.nzavocado.co.nz/research/sustainability/> (Accessed 4 March 2025)
- NZ Avocado. (2024a). *Becoming an avocado grower*. New Zealand Avocado.
<https://industry.nzavocado.co.nz/grow/becoming-an-avocado-grower/> (Accessed 4 March 2025)
- NZ Avocado. (2024b). *Respectful Harvest*. <https://www.respectfulharvest.org> (Accessed 4 March 2025)
- NZ Avocado. (2025). *Primary Growth Partnership (PGP)*. New Zealand Avocado.
<https://industry.nzavocado.co.nz/about-us/funding/primary-growth-partnership-pgp/> (Accessed 4 March 2025)
- New Zealand Herald. (2025). *Growing optimism for the 2025 avocado season*. NZ Herald.
<https://www.nzherald.co.nz/nz/growing-optimism-for-the-2025-avocado-season-in-nz/3ZJGE7YN25CANCU2YYZULD7CWQ/> (Accessed 19 April 2025)
- NZGAP. (2023). *About NZGAP*.
https://www.nzgap.co.nz/NZGAP_Public/About/NZGAP_Public/About/About.aspx?hkey=2bae64bb-4393-4f3a-8e13-e4bd0867aaa5 (Accessed 28 April 2025)
- Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., & Hoagwood, K. (2015). Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research. *Administration and Policy in Mental Health and Mental Health Services Research*, 42(5), 533–544. <https://doi.org/10.1007/s10488-013-0528-y>

- Pomarici, E., Vecchio, R., & Mariani, A. (2015). Wineries' Perception of Sustainability Costs and Benefits: An Exploratory Study in California. *Sustainability*, 7(12), Article 12.
<https://doi.org/10.3390/su71215806>
- Pongthong, P., & Masahiro, Y. (2014). Coffee farmers attitudes toward the 4C process in Chumphon province, Southern Thailand. *Journal of Agricultural Extension and Rural Development*, 6(8), 249–258. <https://doi.org/10.5897/JAERD2013.0575>
- Quartey, C. L. N. K., Osei Mensah, J., Nimoh, F., Adams, F., & Etuah, S. (2021). Choice of certification schemes by smallholder pineapple farmers in Ghana: Analysis of constraints and determinants of adoption. *Journal of Agribusiness in Developing and Emerging Economies*, 13(1), 141–155. <https://doi.org/10.1108/JADEE-02-2021-0046>
- Rietberg, P. (2016). *Barriers to smallholder RSPO certification*. Available for download at: <https://www.evidensia.eco/resources/421/barriers-to-smallholder-rspo-certification-a-science-for-policy-paper-by-the-sensor-programme/>
- Rodthong, W., Kuwornu, J. K. M., Datta, A., Anal, A. K., & Tsusaka, T. W. (2023). Farmers' perceptions and likelihood of adoption of the roundtable on sustainable palm oil practices in Thailand. *Environmental Development*, 47, 100883.
<https://doi.org/10.1016/j.envdev.2023.100883>
- Rosin, C., Campbell, H., & Hunt, L. (2008). Audit Me This! Kiwifruit Producer Uptake of the EurepGAP Audit System in New Zealand. In R. L. Heron & C. Stringer (Eds.), *Agri-Food Commodity Chains and Globalising Networks* (0 ed.). Routledge.
<https://doi.org/10.4324/9781315566276>
- Rosin, M., Ni Mhurchu, C., & Mackay, S. (2024). Implementing healthy food policies in health sector settings: New Zealand stakeholder perspectives. *BMC Nutrition*, 10(1), 119.
<https://doi.org/10.1186/s40795-024-00924-z>
- Sautier, M., Legun, K. A., Rosin, C., & Campbell, H. (2018). Sustainability: A tool for governing wine production in New Zealand? *Journal of Cleaner Production*, 179, 347–356.
<https://doi.org/10.1016/j.jclepro.2017.12.194>
- Secretario, S. (2017). *Revisiting the adoption of the Philippine Good Agricultural Practices (PhilGAP) Certification Programme: A case study of Cavendish banana plantations* [Doctoral dissertation, Massey University, New Zealand]. Massey Research online
<https://mro.massey.ac.nz/items/ffcd6820-32cb-4691-bb7a-3351bbc49b74>

- Seidel-Sterzik, H. (2019). *Bridging the barriers to effective life cycle management uptake: A framework for primary industry sectors*. [Doctoral dissertation, Massey University, New Zealand]. Massey Research Online <https://mro.massey.ac.nz/items/1d1ee697-9c9a-4e26-8cea-6d27288a0f57>
- Seidel-Sterzik, H., McLaren, S., & Garnevska, E. (2018). A Capability Maturity Model for Life Cycle Management at the Industry Sector Level. *Sustainability*, 10(7), 2496. <https://doi.org/10.3390/su10072496>
- Stenton-Dozey, J. M. E., Heath, P., Ren, J. S., & Zamora, L. N. (2021). New Zealand aquaculture industry: Research, opportunities and constraints for integrative multitrophic farming. *New Zealand Journal of Marine and Freshwater Research*, 55(2), 265–285. <https://doi.org/10.1080/00288330.2020.1752266>
- Stranieri, S., Varacca, A., Casati, M., Capri, E., & Soregaroli, C. (2021). Adopting environmentally-friendly certifications: Transaction cost and capabilities perspectives within the Italian wine supply chain. *Supply Chain Management: An International Journal*, 27(7), 33–48. <https://doi.org/10.1108/SCM-12-2020-0598>
- Stringleman, H. (2023). *Huge avocado development draws worldwide interest*. <https://www.farmersweekly.co.nz/markets/huge-avocado-development-draws-worldwide-interest/> (Accessed 3 July 2025)
- Swallow, N., & Barkemeyer, R. (2024). Examining farmers' motivations to engage in low-carbon agricultural practices: A study of New Zealand dairy farmers. *Journal of Rural Studies*, 111, 103440. <https://doi.org/10.1016/j.jrurstud.2024.103440>
- Tey, Y. S., Arsil, P., Brindal, M., Shamsudin, M. N., Radam, A., Hadi, A. H. I. A., Rajendran, N., & Lim, C. D. (2015). A Means-End Chain Approach to Explaining the Adoption of Good Agricultural Practices Certification Schemes: The Case of Malaysian Vegetable Farmers. *Journal of Agricultural and Environmental Ethics*, 28(5), 977–990. <https://doi.org/10.1007/s10806-015-9572-9>
- Thorlakson, T., Hainmueller, J., & Lambin, E. F. (2018). Improving environmental practices in agricultural supply chains: The role of company-led standards. *Global Environmental Change*, 48, 32–42. <https://doi.org/10.1016/j.gloenvcha.2017.10.006>
- Tröster, R. (2018). *The design of voluntary sustainability certification schemes and the role of stakeholder views: Insights from the sector of mineral resources* [Doctoral dissertation, Universität Ulm, Germany]. <https://doi.org/10.18725/OPARU-9546>

- UNCTAD. (2020). *Voluntary Sustainability Standards Assessment Toolkit / UNCTAD*. Available to download at: <https://unctad.org/topic/trade-analysis/voluntary-sustainability-standards/toolkit>
- United Fresh. (2023). *Fresh-Facts December-2023*. Available to download at: <https://unitedfresh.co.nz/technical-advisory-group/fresh-facts>
- Urlich, S. C., & Handley, S. J. (2020). From 'clean and green' to 'brown and down': A synthesis of historical changes to biodiversity and marine ecosystems in the Marlborough Sounds, New Zealand. *Ocean & Coastal Management*, 198, 105349. <https://doi.org/10.1016/j.ocecoaman.2020.105349>
- Valk, O. M. C. van der, & Roest, J. G. van der. (2009). *National benchmarking against GLOBALGAP : Case studies of Good Agricultural Practices in Kenya, Malaysia, Mexico and Chile*. Available for download at: <https://research.wur.nl/en/publications/national-benchmarking-against-globalgap-case-studies-of-good-agri>
- Wilson, D. (2011). The value of sustainability in the New Zealand wine sector. *Wine and Viticulture Journal*. 85-89
- Wongprawmas, R., Canavari, M., & Waisarayutt, C. (2015). A multi-stakeholder perspective on the adoption of good agricultural practices in the Thai fresh produce industry. *British Food Journal*, 117(9), 2234–2249. <https://doi.org/10.1108/BFJ-08-2014-0300>
- Zespri. (2025). *Zespri System Assurance Programmes*. Zespri. <https://www.zespri.com/en-NZ/zespri-system-assurance-program> (Accessed 12 August 2025)

Chapter 3 Towards use of life cycle-based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand

This chapter introduces the LCA study of the avocado sector. It follows on from Chapter 2, which supports using the New Zealand avocado sector as a case study to determine how LCA-based indicators and benchmarks can be developed for a sector-wide agri-food VSS. The following sections have been published as a journal paper titled “Majumdar, S., & McLaren, S.J. (2023). Towards use of life cycle-based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand. *The International Journal of Life Cycle Assessment*. 29, 192-217. <https://doi.org/10.1007/s11367-023-02238-x>”

Abstract

Purpose: A Life Cycle Assessment (LCA) study was undertaken for the orchard stage of the New Zealand 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 hectares 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 hectares. 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.

3.1 Introduction

3.1.1 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 & WHO, 2019; FAO et al., 2023). Current conventional practices in agri-food supply chains are important driving 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 & 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; Jamie Gray, 2018; Ministry for Primary Industries, 2018) and also 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 1,800 growers, who collectively manage more than 4,000 hectares 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 3.1. 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).

Table 3.1 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	Hectares	Volume	Hectares	Volume	Hectares	Volume	Hectares
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 New Zealand	140	271	85	262	66	141	72	149
Total	4811	4145	3617	3937	2979	3795	2235	3839

Given the New Zealand 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.

3.1.2 Avocado LCA research

Thirteen avocado-related LCA resources were identified in the literature (Appendix C, Table C.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 among 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 resources, structures and technology (Cerutti et al., 2014; Nicese & Lazzerini, 2012) and this applies to ornamental plants as well as perennials like walnut trees (Cambria & 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 one 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 & 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) among 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 & 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 New Zealand horticultural sector, most are carbon and water footprints exclusively (Hume et al., 2010; Hume 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. (2021) recently updated the previous carbon footprint studies on kiwifruit, apples, and wine. A preliminary overview of the results of this current avocado LCA study were 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 New Zealand avocados has been conducted yet (as noted in Section 3.1.2). 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 New Zealand in particular. The study could help the industry association plan its environmental improvement strategy going forward and could help individual growers as well.

3.2 Methodology

3.2.1 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 hectare 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, changes 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.

3.2.2 Impact categories and assessment methods

The 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 guidelines (EPD International, 2022), the following methods were used:

- Climate Change – Global warming potential (kg CO₂ 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 factors²¹)
- 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 phosphorous is a limiting factor in freshwater environments. But freshwater environments in New Zealand are often limited by both nitrogen and phosphorous, and therefore there is an inherent methodological uncertainty/limitation when using ReCiPe 2016 for New Zealand conditions (Payen & Ledger, 2017). Therefore, the CML 2001 method was used in this study; it assumes 100% of the emissions of both nitrogen and phosphorous contribute to eutrophication impacts and therefore provides a ‘worst-case’ scenario.

For water use, AWARE characterisation factors are provided on a national, sub-national, and watershed level, and for agricultural, non-agricultural, and unspecified water use. 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 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

²¹ USEtox provides a distinction between ‘recommended’ and ‘interim’ characterisation factors, based mainly on the applicability to respective substances or the availability/quality/reliability of input data. However, ideally, it is recommended that both be included (Life Cycle Initiative, 2023).

emission flows for most of the pesticides used in the avocado orchards. For the fate of pesticides, it was assumed that 100% of the AI emissions from all applied pesticides went to agricultural soil (following EPD International (2019), Section 4.10.2.6, p 16), and as discussed in (Fantke, 2019; Nemecek & Schnetzer, 2012; Renaud-Gentié et al., 2014; Nemecek et al., 2020). However, as current 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.

3.2.3 Sampling strategy and data collection

3.2.3.1 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 two years (2018-19 and 2019-20) were considered – and most orchards had at least four years' data.

The selected orchards were further categorised by production practices (best practice, good practice, and standard practice), and by orchard area (big (>5ha), medium (2.0 – 5ha) and small (<2ha)). The orchards identified for the baseline model spanned a cumulative area of 281 hectares. 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):

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

Where 'I' equals 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 two years; and then divided by the number of years minus 1 (n). For the New Zealand avocado sector, this value was calculated for each year between 2016-2020.

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'²² orchards 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). While this represented <3% of the total 'population' (1,800 growers in the country), when the total production of these orchards is compared to the national avocado production, this sample represents 19% of the New Zealand avocado sector. Moreover, stratified sampling is a random sampling method based on probability, in which the sample is divided into two or more groups based on multiple common attributes/strata. Stratified sampling allows for greater representativeness and precision than simple random sampling (Zampori & Pant, 2019). Thus, the stratified sampling process used in this study ensured representativeness across different orchard practices, sizes and regions, providing a holistic rather than a siloed view of the sector. Since the main purpose of the LCA study was to develop benchmarks by quantifying the environmental impacts and determining hotspots for the sector as a whole, rather than compare alternative product systems, it was considered to be fit for purpose i.e., the data collected are considered to be broadly representative of the range of New Zealand avocado production systems.

²² '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.

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.

3.2.3.2 Orchard lifespan

Perennial fruit trees have much longer lifespans than field crops (10->50 years), depending on the fruit species. As noted in Section 3.1.2, most published fruit-related LCA studies consider only one 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 under-estimated 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 production²³; 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 3.2. Inputs for the orchard establishment

²³ 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.

stage were collected from each of the four supra-massive orchards (spread over 489 hectares), their impacts assessed separately and then averaged.

Table 3.2 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
Year 1-3 – Orchard establishment	1,887*
Year 4-47 – Commercial production	14,723**
Year 48-50 – Orchard senescence	1,887*

** Average yield of four supra-massive orchards in the Far North during Years 1-3; ** Average yield of baseline model orchards in the Far North*

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.

3.3 Inventory analysis

3.3.1 Inventory data for baseline model

3.3.1.1 Agrichemicals

Data on agrichemical use was obtained from the spray diaries completed by orchards as part of New Zealand Avocado's Avogreen programme. The calculation and analysis of agrichemical emissions was based on the Active Ingredient (AI) of the pesticide products (Appendix C, Table C.2), whereas production impacts were based on the inputs for the formulated products. For insecticides, there are very limited inventory datasets available, and none were 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) (Appendix C, Table C.3); their impacts were calculated based on the copper content as the AI. As many agrichemical products for New Zealand 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 Section 3.2.2, all pesticide AIs were modelled for 100% emission to agricultural soil.

3.3.1.2 Fertilisers/soil conditioners

Fertiliser and soil conditioner use data was obtained from the spray diaries completed by New Zealand 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 (Appendix C, Table C.4). For blended and complex fertilisers, the component quantities were calculated separately and used as inputs to the orchard processes, using the straight fertiliser datasets (Appendix C, Table C.5, C.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 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 New Zealand) (Section 3.3.1.1) with a few exceptions (Appendix C, Table C.7):

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

The nitrogen, phosphorous, and carbon dioxide emissions due to fertiliser application were modelled using emission factors as noted in Appendix C, Table C14. Nitrogen and phosphorous emissions from use of fertilisers were modelled using the guidelines in EPD International (2019). For CO₂ 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 and 0.48 kg CO₂/kg of fertiliser
- Coated and non-coated urea fertilisers: 1.594 kg CO₂/kg of N fertiliser.

Compost was used on two orchards. The emission factors for compost production were 0.004 kg CH₄/kg of compost, and 0.00024 kg N₂O/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 CH₄ 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 0.01 kg N₂O/kg of compost was used (IPCC, 2006). With regards 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 metals-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.

3.3.1.3 Fossil fuel and electricity

The main activities carried out on orchards are listed in Table 3.3. 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.

Table 3.3 Machinery and fuel generally used for activities on avocado orchards

On-Orchard Activity	Machinery and Fuel Used for Activity	Fuel use rates (L/hour)
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*	-
Other on-orchard transport	Quad bike – petrol	2
	Tractor – diesel	4.5
	Motorbike – petrol	2.5
	Forklift – Diesel	3
	Forklift – LPG	4

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

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 3.3); 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.

3.3.1.4 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.

3.3.2 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 3.4).

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

Table 3.4 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	20500
	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/hr)

3.4 Results

3.4.1 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. Interquartile Range (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. Table 3.5, Table 3.6, and Table 3.7 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 variable fertiliser and soil conditioner inputs respectively. Diesel 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 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.

Table 3.5 Average agrichemical use on sampled orchards for the study regions

Insecticide Use – Total Product Applied (kg or L/ha)					Insecticide Use – Total AI Applied (kg or L/ha)			
	Minimum	Maximum	Median	IQR	Minimum	Maximum	Median	IQR
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 – Total Product Applied (kg or L/ha)					Herbicide Use – Total AI Applied (kg or L/ha)			
	Minimum	Maximum	Median	IQR	Minimum	Maximum	Median	IQR
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 – Total Product Applied (kg or L/ha)					Fungicide (Cu-Based) Use – Total AI Applied (kg or L/ha)			
	Minimum	Maximum	Median	IQR	Minimum	Maximum	Median	IQR
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 – Total Product Applied (kg or L/ha)					Mineral Oil Use – Total AI Applied (kg or L/ha)			
	Minimum	Maximum	Median	IQR	Minimum	Maximum	Median	IQR
Far North*	3.26E+01	8.77E+01	6.01E+01	-	2.68E+01	6.88E+01	4.77E+01	-
Mid North*	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

Table 3.6 Average fertiliser and soil conditioner use on sampled orchards for the study regions

Fertiliser Use – Total Product Applied (kg or L/ha)				
	Minimum	Maximum	Median	IQR
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
Fertiliser Use – Total Nitrogen Applied (kg/ha)				
	Minimum	Maximum	Median	IQR
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
Fertiliser Use – Total Phosphorous Applied (kg/ha)				
	Minimum	Maximum	Median	IQR
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)				
	Minimum	Maximum	Median	IQR
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 3.7 Average fuel, water, and electricity use on sampled orchards for the study regions

Total Diesel Use (L/ha)				
	Minimum	Maximum	Median	IQR
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)				
	Minimum	Maximum	Median	IQR
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 (m³/ha)				
	Minimum	Maximum	Median	IQR
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)				
	Minimum	Maximum	Median	IQR
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

3.4.2 Baseline model Life Cycle Impact Assessment (LCIA)

The regional and national impact scores²⁴ are presented in Table 3.8.

Table 3.8 National impact scores for New Zealand–produced avocados

	Climate Change (kg CO₂ eq./kg avocados)	Eutrophication (kg Phosphate eq./kg avocados)	Water Use (m³ 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

3.4.2.1 Climate change

The main contributing sub-stages/inputs to the climate change impact category in all three regions are fuel and fertilisers (Figure 3.1). The fuel use impacts are primarily due to CO₂ emissions from fuel combustion (mainly diesel) in agricultural machinery used on orchards.

All fertiliser-related impacts are due to emissions of CO₂ and N₂O 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 (Figure 3.2). Figure 3.3 shows the variability between relative contributions (%) of production and transport of individual fertilisers and soil conditioners to overall non-application climate change impacts.

²⁴ The water use results use sub-national factors and are therefore updated from Majumdar et al. (2022).

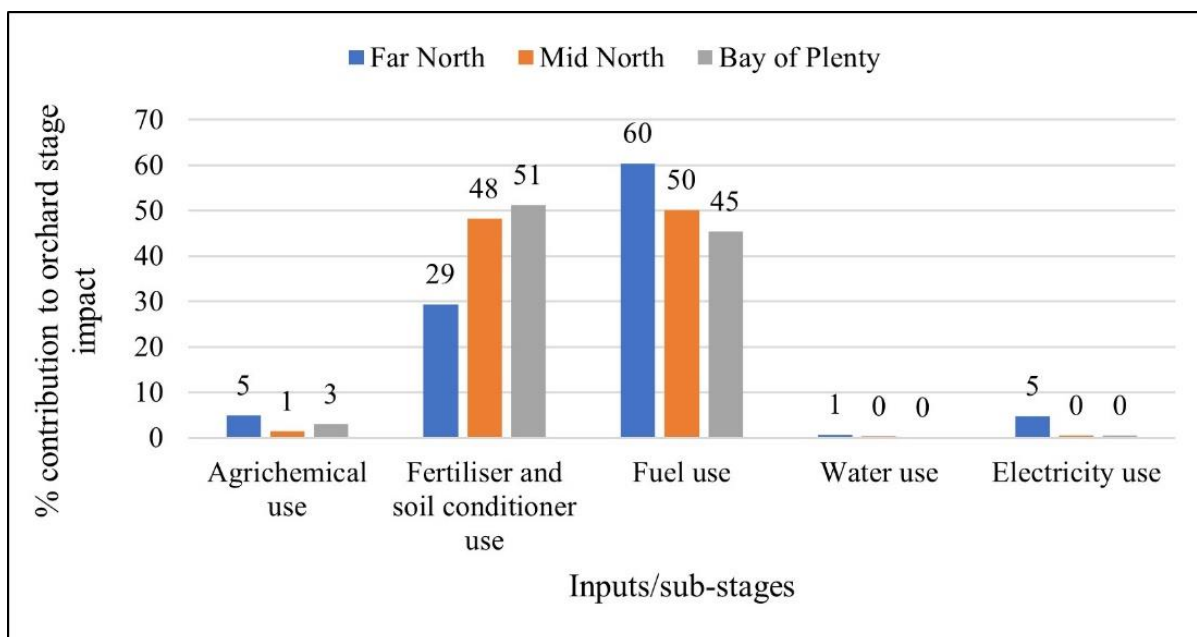


Figure 3.1 Contribution (%) of inputs/sub-stages to overall climate change impact of the orchard stage

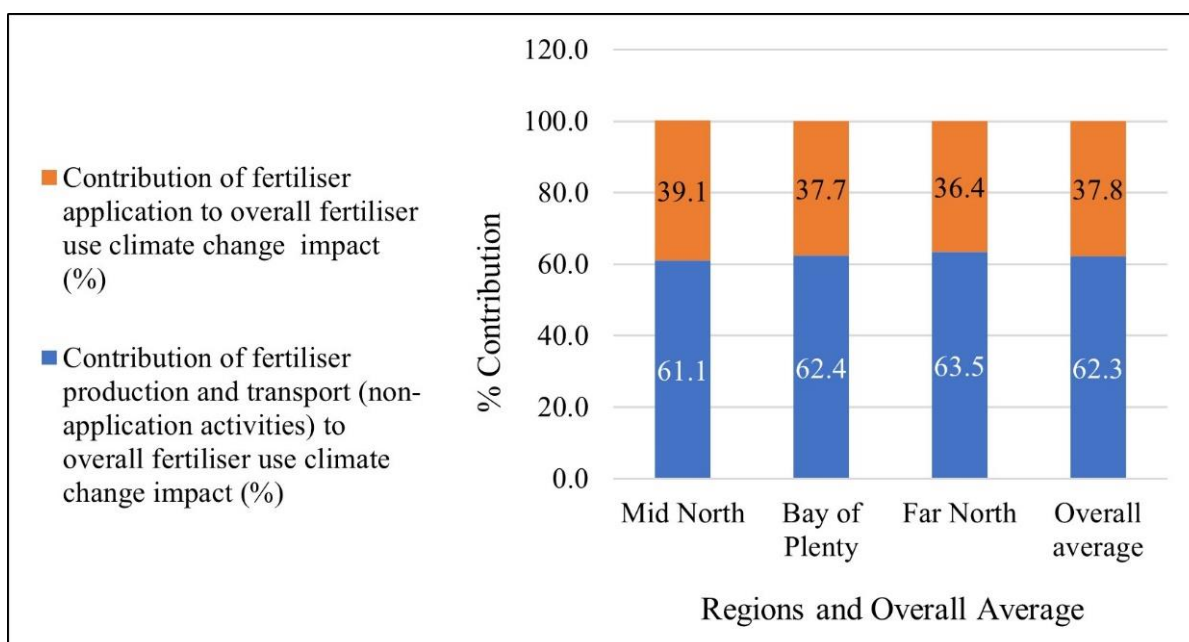


Figure 3.2 Contribution of fertiliser production, transport and use (application) to overall fertiliser use impacts on orchards

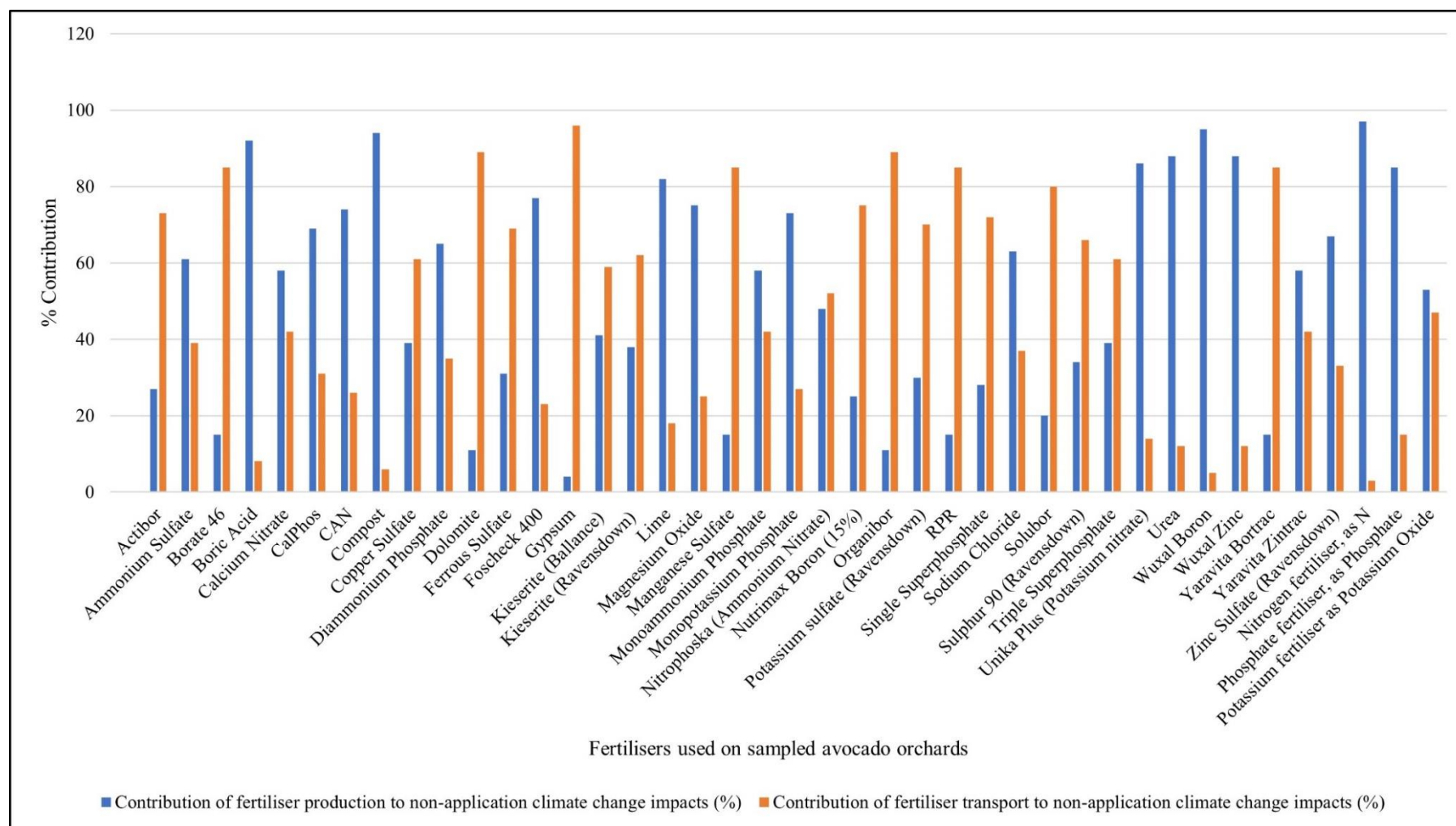


Figure 3.3 Relative contributions (%) of production and transport of individual fertilisers and soil conditioners to overall non-application climate change impacts

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 CO₂ 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 New Zealand avocados developed in this study (0.43 kg CO₂ 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 (Section 3.2.1).

3.4.2.2 Eutrophication

Fertiliser and soil conditioner use contribute the most to the eutrophication impact category in all three regions (Figure 3.4), followed by fuel use. The majority of the impacts are from fertiliser application (Figure 3.5), 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.

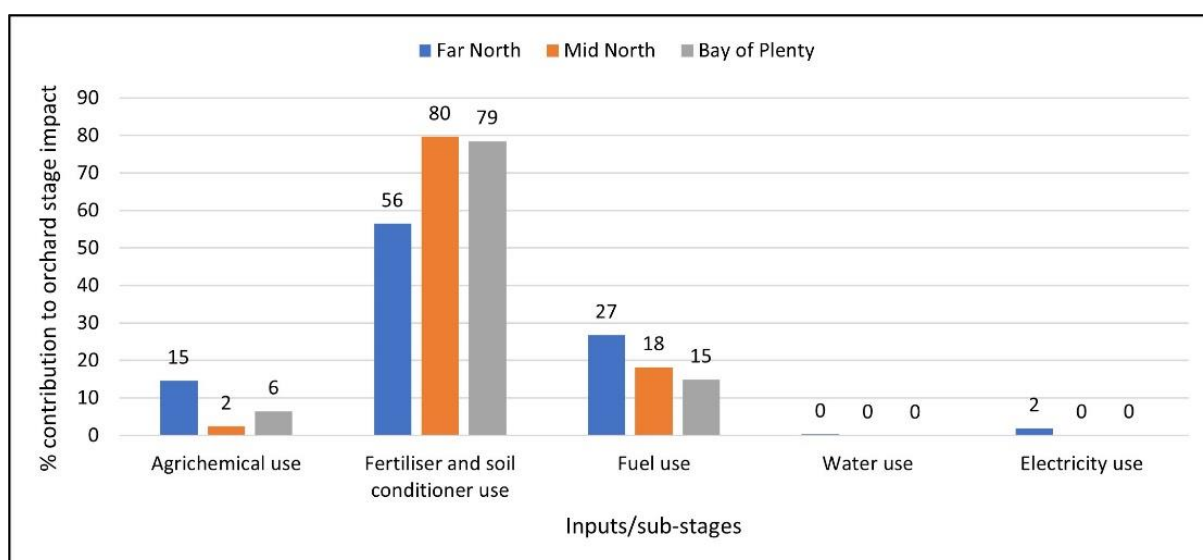


Figure 3.4 Contribution (%) of inputs/sub-stages to overall eutrophication impact of the orchard stage

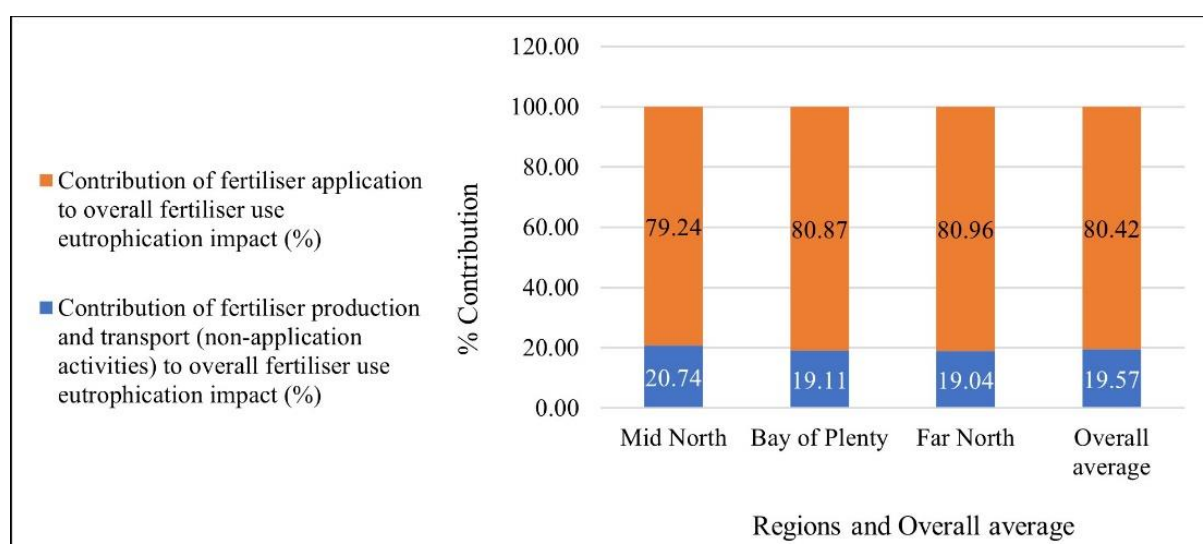


Figure 3.5 Contribution of fertiliser application, and non-application activities (production and transport) to overall fertiliser use eutrophication impact on orchards

3.4.2.3 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, 0.2, and 0.14 m³ world equivalent./kg avocados respectively). Figure 3.6 shows the contribution (%) of direct and indirect water use 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. This trend deviates from other agricultural LCA studies, wherein direct water use accounts for majority of the impacts generally. The reason for this deviation is

that sub-national AWARE characterisation factors were used for direct water use on orchard – in contrast, the higher national level factors were used for the embodied (indirect) water use as disaggregation of water source by region was not possible at those stages. When using the national level factor for both the direct and indirect water use, the on-orchard water use becomes the major driver of impacts as shown in Appendix C, Figure C1.

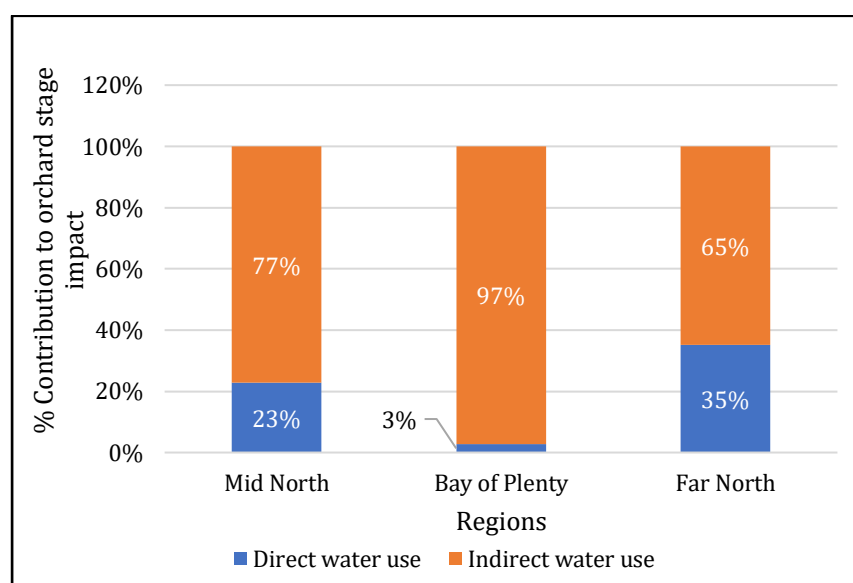


Figure 3.6 Relative contributions of direct and indirect water use to the total impact score for the orchard stage for the three regions (using the sub-national agricultural CF for water use)

3.4.2.4 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 (Figure 3.7). The difference in relative contributions of these two types of inputs largely reflects the varying quantities of copper-based fungicides used on orchards in the different regions.

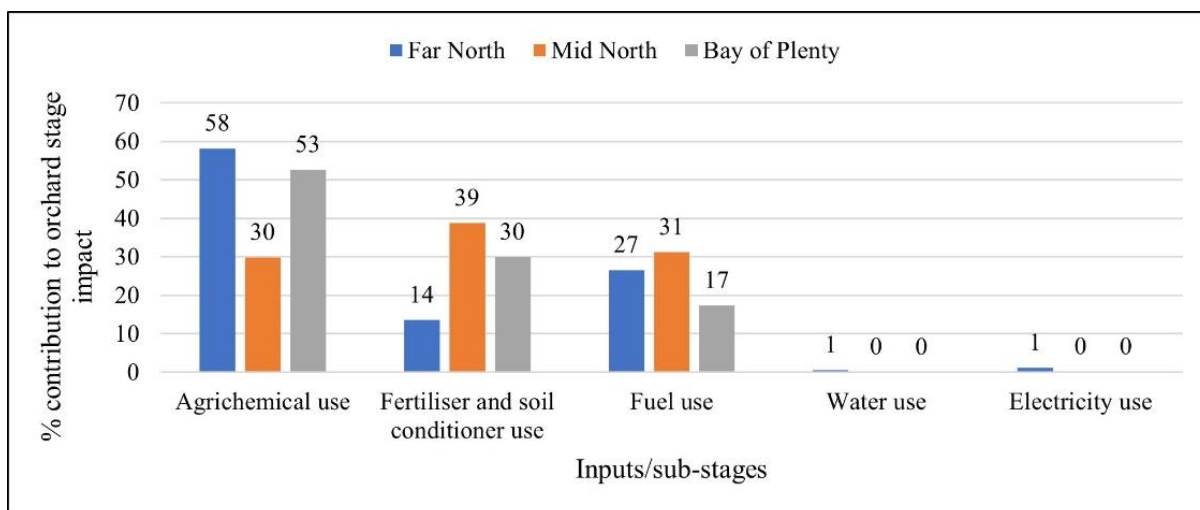


Figure 3.7 Contribution (%) of Inputs/sub-stages to overall freshwater ecotoxicity impact of the orchard stage

3.4.2.5 Terrestrial ecotoxicity

Terrestrial ecotoxicity impacts are mainly due to emissions of heavy metals (particularly copper) to air during the manufacture of agrichemicals and fertilisers (Figure 3.8). Fuel use is also a contributor to these impact category results.

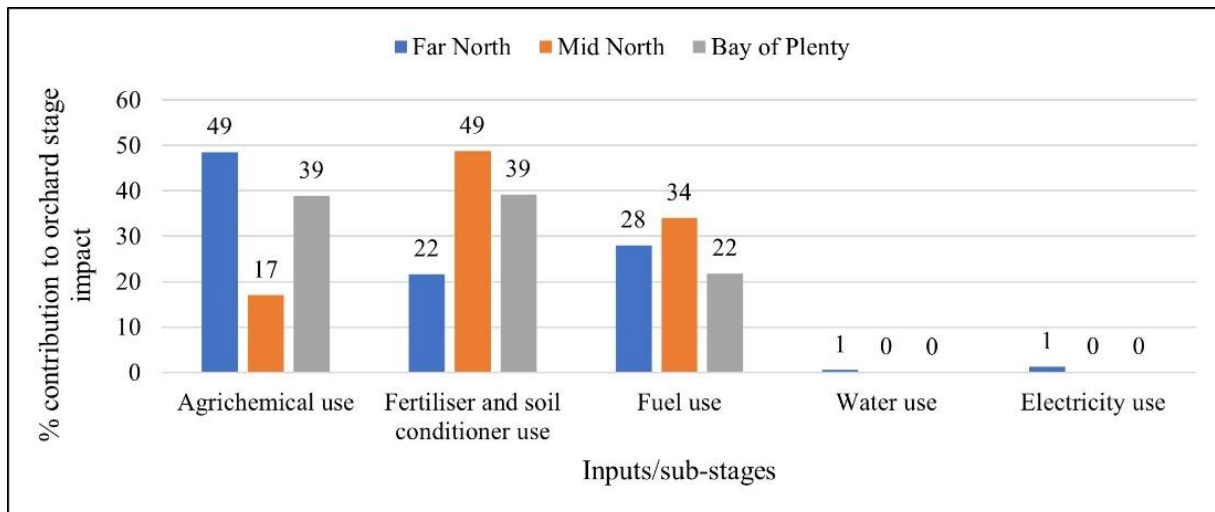


Figure 3.8 Contribution (%) of Inputs/sub-stages to overall terrestrial ecotoxicity impact of the orchard stage

3.4.3 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 3.9). The Mid North showed the highest variability among orchards in the climate 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.

Table 3.9 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

3.4.4 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 (Figure 3.9). The climate change and eutrophication scores decrease as orchard yields increase (Figure 3.9(a), (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 (Figure 3.9 (c) to (e)).

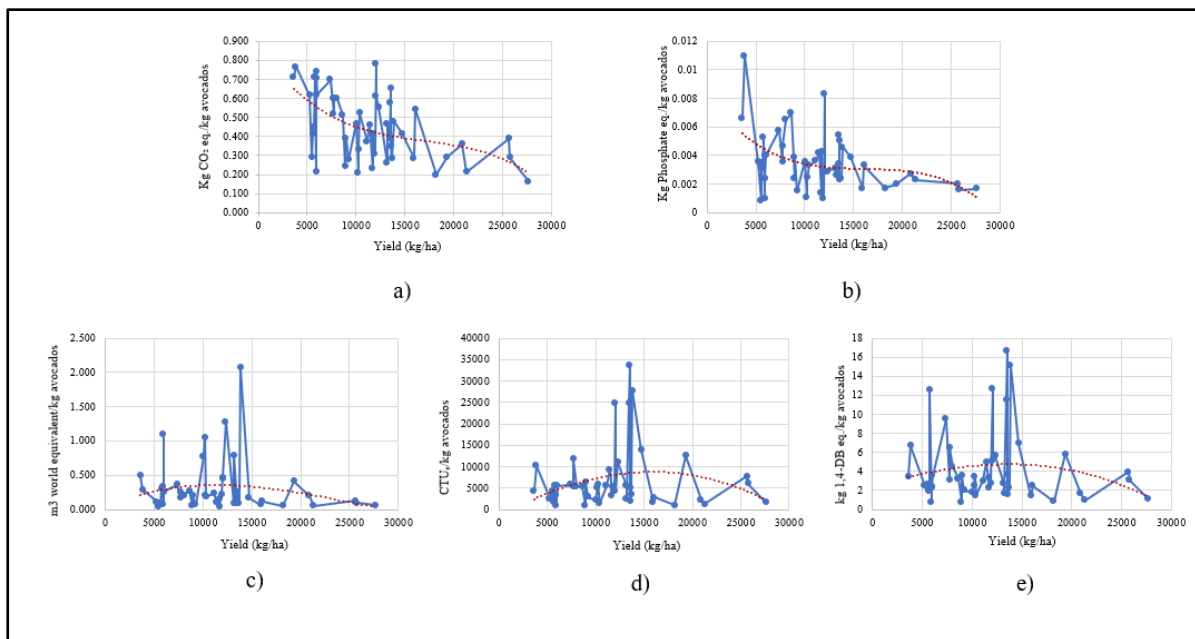


Figure 3.9 Co-relation between impact category scores and yields (kg/hectare) of individual orchards in the baseline model (a-climate change; b-eutrophication; c-water use; d-freshwater ecotoxicity; and e-terrestrial ecotoxicity)

3.4.5 Impacts across orchard lifespan

The contribution of each orchard stage to the total impacts scores for the 50-year orchard lifespan are shown in Figure 3.10, 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.

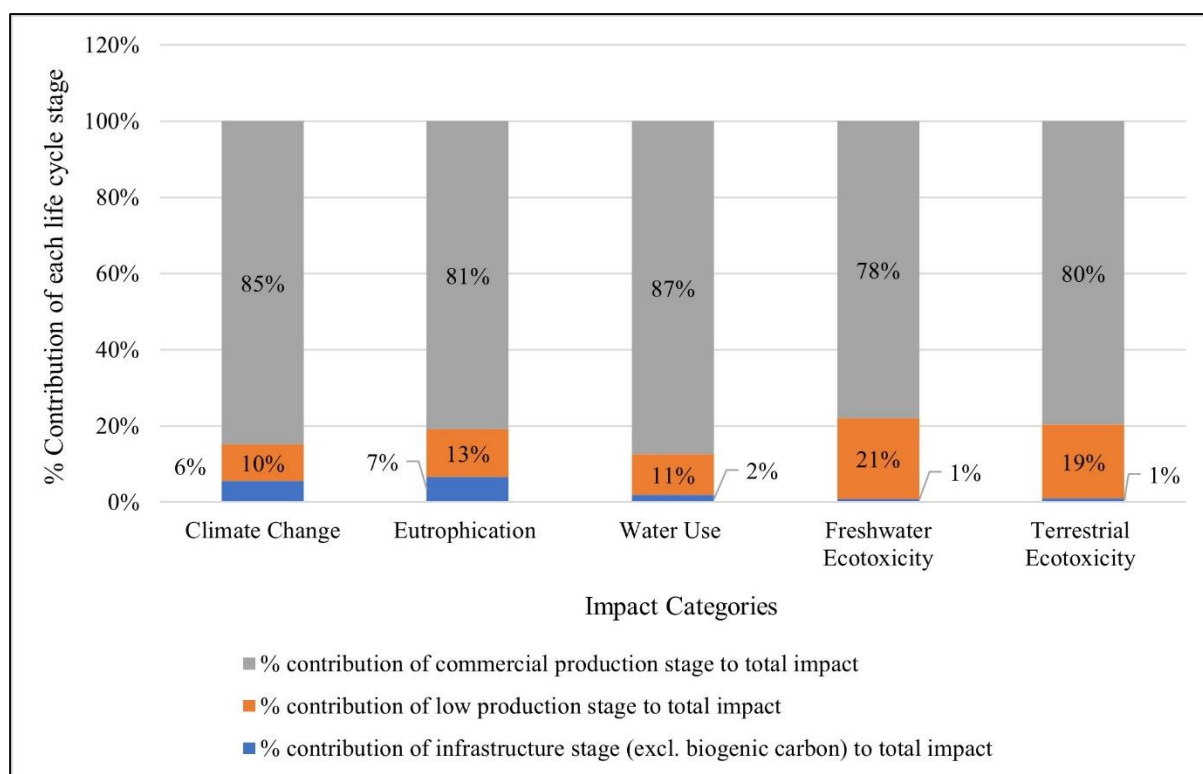


Figure 3.10 Contribution of each orchard stage to total impacts across orchard lifespan (calculated for one hectare over 50 years), modelled for Far North orchards

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 hectare of orchard area, divided by the total avocado production over the same time period (Table 3.10).

Table 3.10 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)*	% Increase of weighted average from baseline
GWP (kg CO₂ 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	3.30E + 02	1.95E + 03	2.41E + 03	4.00E – 03	3.00E – 03	26
Water Use (m³ 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

*Values for a commercially productive year

The average impact per kg avocados is 13-26% higher than the baseline results for the five impact categories.

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

3.4.6 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 3.11 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.

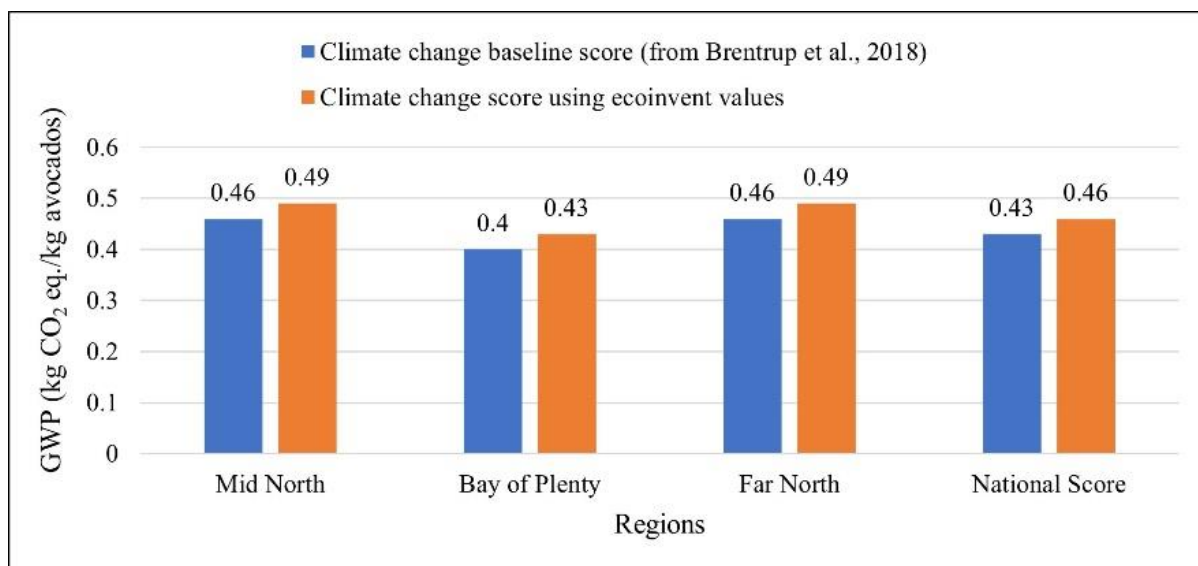


Figure 3.11 Change in climate change impact scores from baseline, when using the original ecoinvent datasets for fertilisers, instead of the Brentrup et al. (2018) values used in the baseline

For use of fertilisers, Appendix C, Table C13 lists the emission factors for use of nitrogen fertilisers provided in EPD International (2019) and Ministry for the Environment (2020). The table shows that the climate change emission factors for all fertilisers listed in the EPD International (2019) guidelines are higher than the corresponding Ministry for the Environment (2020) values (which are provided just for urea (no UI), urea (UI) and non-urea fertilisers (generic)) except for 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 3.12 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.

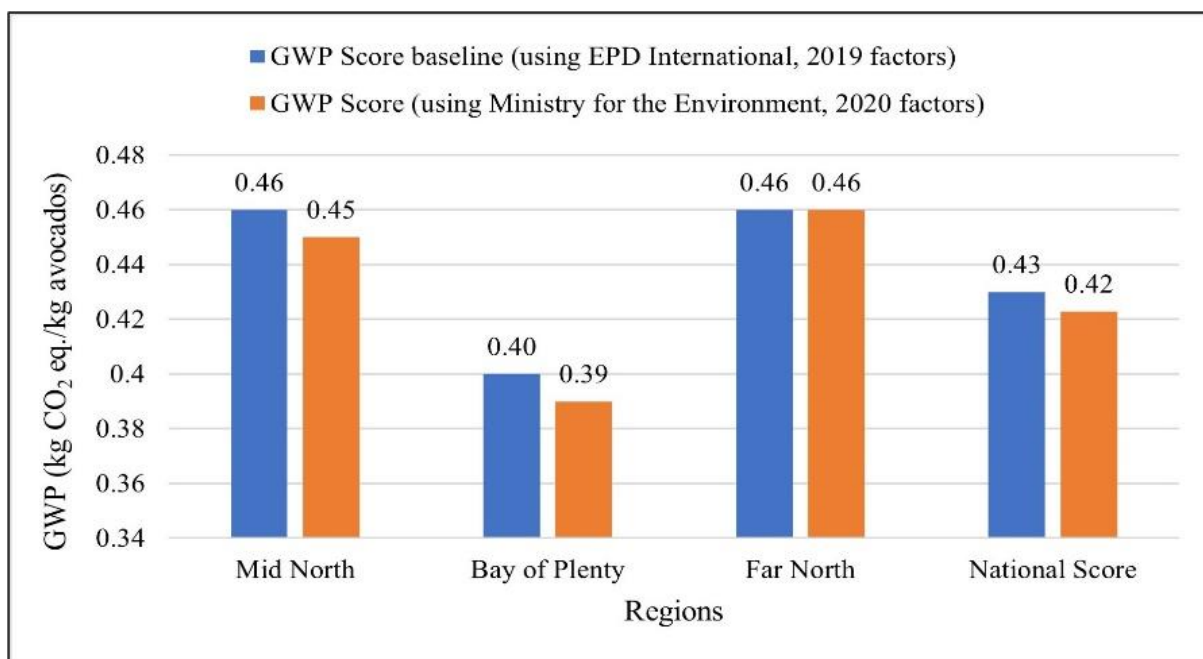


Figure 3.12 Climate change impact scores for baseline, and when using the Ministry for the Environment (2020) emission factors for nitrogen fertiliser use

3.5 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.

3.5.1 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 literature. 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 CO₂ eq./kg avocados) (Table 3.11). Although all the studies used the same unit of measurement (kg CO₂ 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 & Akbari, 2023).

Table 3.11 Climate change impact scores from different avocado-related LCA studies identified in the literature review

Citation	Climate change impact (kg CO₂ 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 and Co. (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)

In contrast to these two papers, in this study fertiliser/soil conditioner 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 New Zealand'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 source 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 & Johnsen, 2019; Vatsanidou et al., 2020). Horticultural LCA studies in New Zealand for kiwifruit and 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).

With respect to eutrophication impacts of avocados, only two studies were found. Esteve-Llorens et al (2022) and Frankowska et al. (2022) noted values similar to those obtained in this study (0.001 and 0.002 kg Phosphate eq./kg fruit respectively). With respect to the relative significance of absolute eutrophication values of avocados compared with other crops or agricultural products, a comparison can be made with published literature only when similar system boundaries and impact assessment methods are used. This is challenging as these aspects are highly variable in different studies, and therefore, only limited comparison is possible. When assessing eutrophication impacts to the farm gate and using the CML method as was done in the current study (or converting kg P eq. values used by the ReCiPe method to kg Phosphate eq.), the eutrophication impacts of other perennial crops are very similar to the current study (e.g. 0.003, 0.004, and 0.002-0.006 kg Phosphate eq./kg product for pistachios, almonds, and plums respectively) (Bartzas et al., 2017; Svanes and Johnsen, 2019; Yan et al., 2023), whereas apples have a lower impact by an order of magnitude (0.0001-0.0004 kg Phosphate eq./kg fruit) (Bartzas et al., 2017; Basset-mens et al., 2016; Keyes et al., 2015; Longo et al., 2017). Bananas had similar impact values to New Zealand avocados (0.004 kg Phosphate eq./kg fruit) (Coltro and Karaski, 2019), whereas other vegetables had much lower impacts (e.g. 0.0005, 0.00007 and 0.00003-0.0001 kg Phosphate eq./kg of potatoes, cucumbers and tomatoes respectively) (Bojaca et al., 2014; Khoshnevisan et al., 2014; Abdelhamid et al., 2025). With respect to stagewise contribution analysis, 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 regards 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 New Zealand 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 m³/ha compared with the lowest value of 8285 m³/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 subnational 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 m³ world equiv./kg avocados) when using the national (unspecified) rather than subnational AWARE characterisation factors. The change is most significant for the Bay of Plenty and least for the Far North, since the regional characterisation factor for the Bay of Plenty was much smaller than the national one, compared to the Far North value. This trend was noted in another study on New Zealand dairy as well (Payen et al., 2018). Using region-specific rather than national-average characterisation factors

led to a large reduction in the estimated water footprint of Waikato milk, which fell by 73% from 0.08 to 0.02 m³ world eq. per kg fat and protein corrected milk (FPCM). By comparison, the water footprint of Canterbury milk decreased by only 8%, from 1.7 to 1.5 m³ world eq per kg FPCM. This difference can be attributed to the fact that Waikato's regional characterisation factor is substantially lower than the New Zealand average, while Canterbury's regional factor is broadly comparable to it. This sensitivity of water use impact scores to localised AWARE characterisation factors was also noted in the Peruvian avocado study by Esteve-Llorens et al. (2022). With respect to other agri-food products, water use impact assessments using the AWARE method were limited – values were noted in literature for rice, sugarcane, maize, and cassava in Thailand (0.05-3.66, 0.51-7.99, 1.09-8.28, and 1.65-30.3 m³ world-eq. per kg product) (Kaewmai et al., 2021) and pork in Finland (0.69 m³ world-eq. per kg carcass weight) (Hietala et al., 2024).

3.5.2 Towards the use of continuous improvement indicators for New Zealand avocado orchards

This LCA study resulted in the development of regional and national level impact scores for New Zealand 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 New Zealand avocado production. Other work has 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 development of such indicators and benchmarks.

3.5.2.1 Variability between orchards

There was considerable variability between orchards in terms of inputs (Section 3.4.1, Table 3.5-Table 3.7) and impacts (Section 3.4.3, Table 3.9). To further illustrate this point, Figure 3.13 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.

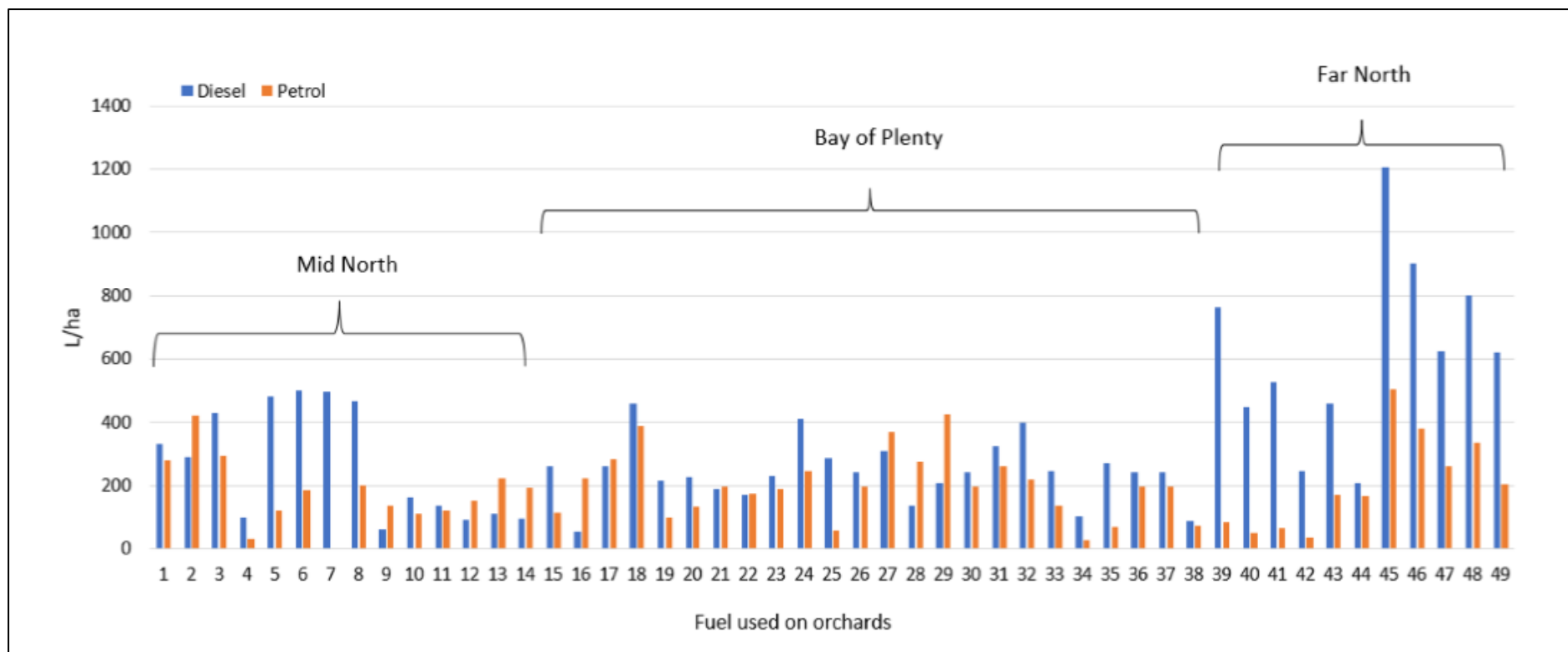


Figure 3.13 Fuel use (petrol and diesel) on each of the 49 orchards in this study

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 two or three 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 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 & Nemecek, 2018; Cucurachi et al., 2019; Green et al., 2021). Therefore, careful consideration should be given to the variability amongst New Zealand 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/or management regimes (e.g. the large commercial operations in Northland and the smaller family run businesses in the Bay of Plenty).

3.5.2.2 Productivity and eco-efficiency as indicators

The co-relation analysis between orchard productivity and environmental impact scores (Section 3.4.4) 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 New Zealand 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 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 New Zealand-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 New Zealand avocado sector. However, when calculating the sector’s IBI (see Section 3.2.3.1), if the orchard yield increases three 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 two-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.

3.5.2.3 *Lifespan of orchard*

The results of the impact assessment across the whole orchard life (Section 3.4.5) 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 is ‘in the

past' for most growers and its assessment is irrelevant in terms of improvement options. Also, as mentioned in Section 3.1.2, 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. Figure 3.14 - Figure 3.18 demonstrates this approach for the four supra-massive orchards in the Far North and also shows 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 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 impacts 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 different management.

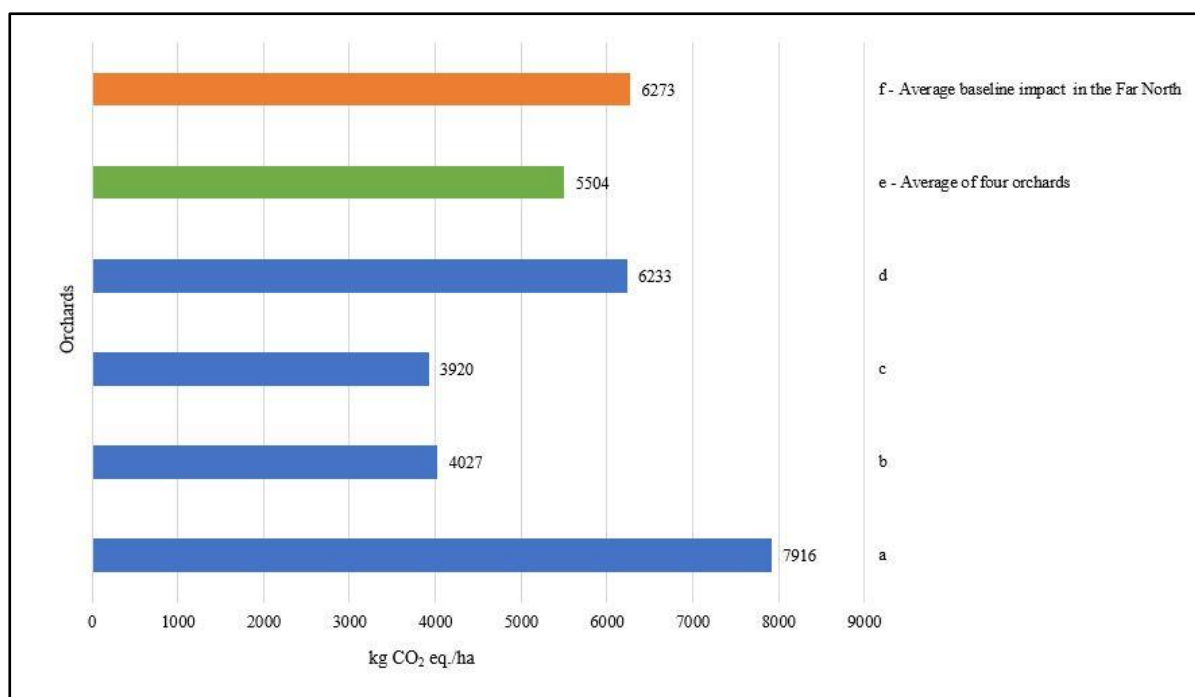


Figure 3.14 Climate change impacts per hectare of the four 'supra-massive' orchards (a to d), average of the four orchards (e), compared to the average environmental impact per hectare of baseline orchards in the Far North (f)

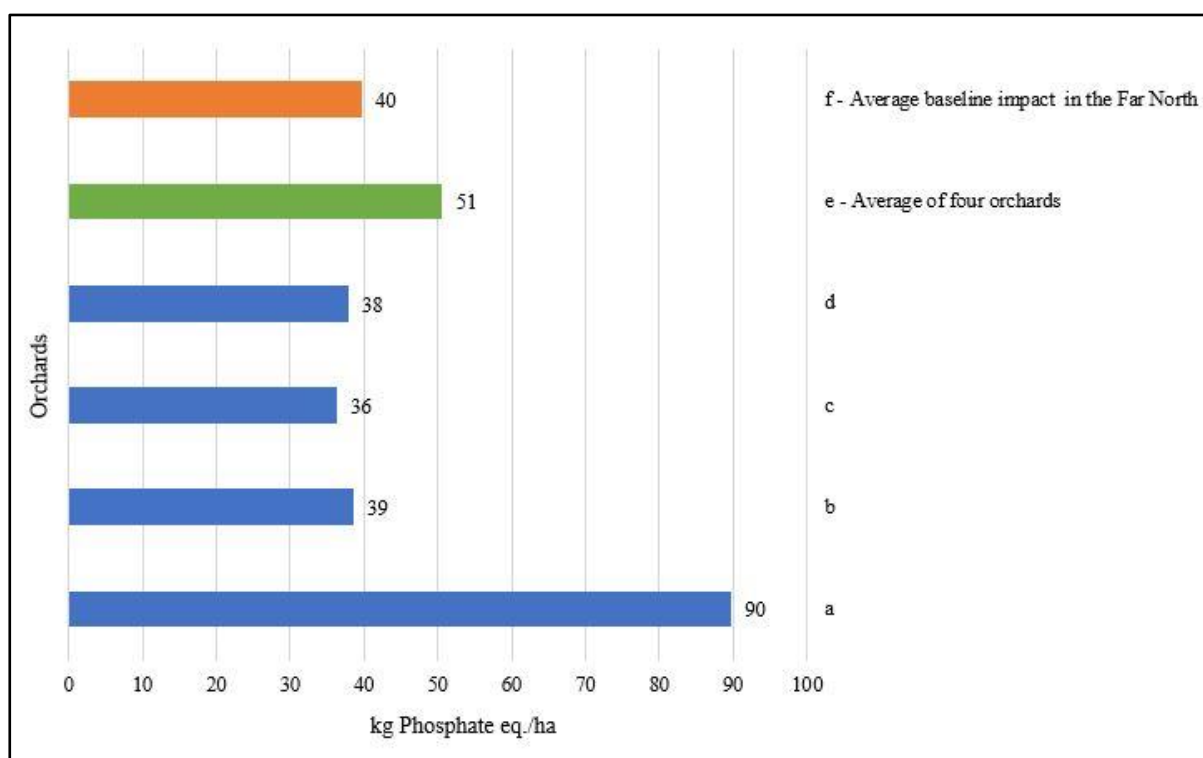


Figure 3.15 Eutrophication impacts per hectare of the four 'supra-massive' orchards (a to d), average of the four orchards (e), compared to the average environmental impact per hectare of baseline orchards in the Far North (f)

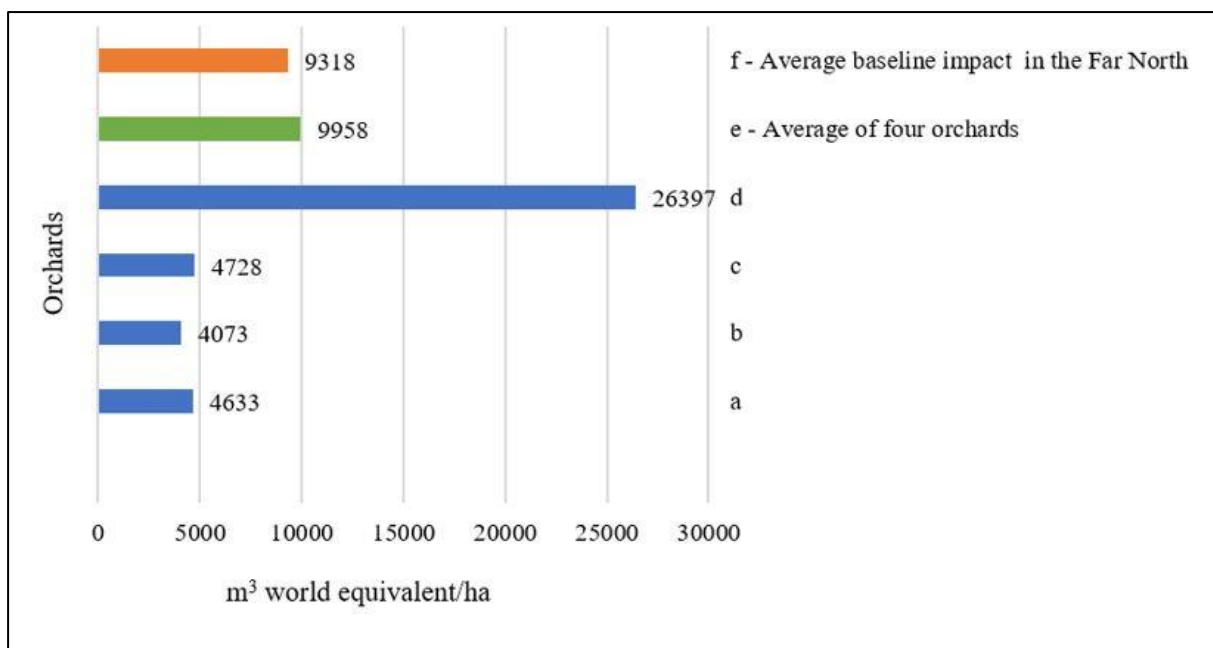


Figure 3.16 Water use impacts per hectare of the four 'supra-massive' orchards (a to d), average of the four orchards (e), compared to the average environmental impact per hectare of baseline orchards in the Far North (f)

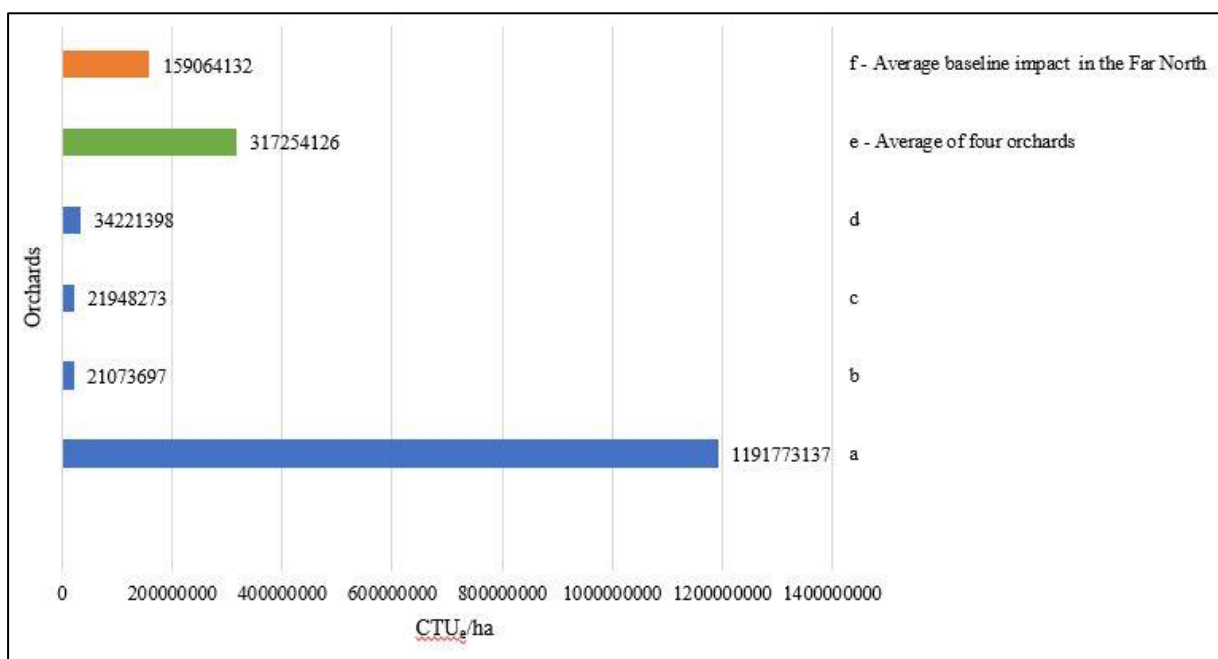


Figure 3.17 Freshwater ecotoxicity impacts per hectare of the four 'supra-massive' orchards (a to d), average of the four orchards (e), compared to the average environmental impact per hectare of baseline orchards in the Far North (f)

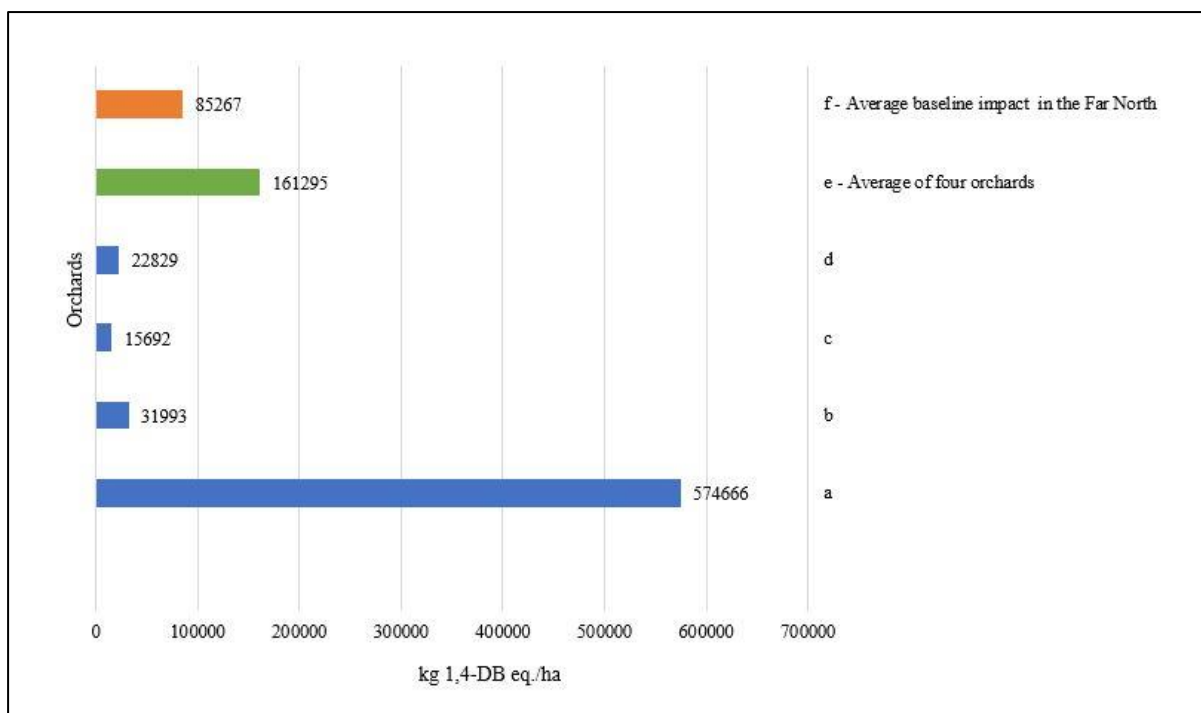


Figure 3.18 Terrestrial ecotoxicity impacts per hectare of the four 'supra-massive' orchards (a to d), average of the four orchards (e), compared to the average environmental impact per hectare of baseline orchards in the Far North (f)

3.5.2.4 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 un-topped 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 (Section 3.2.2). However, in the absence of a suitable site-specific method, the CML 2001 method is recommended as a precautionary approach (Payen & Ledgard, 2017).

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 & Lenoir, 2020). Moreover, an annual water use value was collected for this study period of 2018-19, 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 future to offer more temporal and spatial resolution. These characterised water scarcity indicator results (using subnational-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 (Section 3.5.1).

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; Renaud-Gentié 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 & Hauschild, 2006; Renaud-Gentié 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 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., 2021). Finally, additional targeted data collection is recommended for any future avocado-related research in New Zealand. This includes data related to the ‘source of origin’ of fertilisers and agrichemicals used on New Zealand avocado orchards, as well as collecting soil conditioning data over several years which can then be used to calculate average annual inputs.

3.6 Conclusion

The New Zealand 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 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, 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 New Zealand. Such refined indicators can support individual orchards to improve their environmental performance, while also communicating the environmental profile of New Zealand avocado production at national and international levels.

References

- Abdelhamid, M.A., Baraka, S.M., Ali, K.A.M. *et al.* Energy and Life Cycle Assessment of Potato Production under Groundwater and Surface Water Irrigation Systems in Egypt: A Pathway to Sustainable Agriculture. *Potato Research* 68, 3447–3473. <https://doi.org/10.1007/s11540-025-09885-7>
- Alaphilippe, A., Boissy, J., Simon, S., & Godard, C. (2016). Environmental impact of intensive versus semi-extensive apple orchards: Use of a specific methodological framework for Life Cycle Assessments (LCA) in perennial crops. *Journal of Cleaner Production*, 127, 555–561. <https://doi.org/10.1016/j.jclepro.2016.04.031>
- Apparao, D. J., et al. (2023). *Situation and outlook for primary industries 2023*. Ministry of Primary Industries. <https://www.mpi.govt.nz/science/open-data-and-forecasting/situation-and-outlook-for-primary-industries-data/>
- Astier, M., Merlín-Uribe, Y., Villamil-Echeverri, L., Garcíarreal, A., Gavito, M. E., & Masera, O. R. (2014). Energy balance and greenhouse gas emissions in organic and conventional avocado orchards in Mexico. *Ecological Indicators*, 43, 281–287. <https://doi.org/10.1016/j.ecolind.2014.03.002>
- Australian Bureau of Statistics. (2023). *Measures of spread*. <https://www.abs.gov.au/statistics/understanding-statistics/statistical-terms-and-concepts/measures-spread> (Accessed 19 September 2023)
- Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., & Williams, A. (2009). *How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050*. WWF-UK.
- Barry, M. T. (2011). *Life cycle assessment and the New Zealand wine industry: A tool to support continuous environmental improvement* [Master's thesis, Massey University, New Zealand]. Massey Research Online. <https://mro.massey.ac.nz/items/95e2dc84-1144-4e0b-9661-04c093141bf9>
- Bartl, K., Verones, F., & Hellweg, S. (2012). Life cycle assessment-based evaluation of regional impacts from agricultural production at the Peruvian Coast. *Environmental Science & Technology*, 46(18), 9872–9880. <https://doi.org/10.1021/es301644y>
- Bartzas, G., Vamvuka, D., and Komnitsas, K. (2017). Comparative life cycle assessment of pistachio, almond and apple production. *Information Processing in Agriculture* 4, 188-198. <http://dx.doi.org/10.1016/j.inpa.2017.04.001>

- Basset-Mens, C., Vannière, H., Grasselly, D., Heitz, H., Braun, A., Payen, S., Koch, P., & Biard, Y. (2016). Environmental impacts of imported and locally grown fruits for the French market: A cradle-to-farm-gate LCA study. *Fruits*, 71(2), 93–104. <https://doi.org/10.1051/fruits/2015050>
- Beef + Lamb NZ. (2018). *Environment strategy and implementation plan 2018–2022*. <https://beeflambnz.com/sites/default/files/levies/files/Env-strategy-Imp-plan.pdf> (Accessed 3 July 2023)
- Bell, E. M., Stokes-Draut, J. R., & Horvath, A. (2018). Environmental evaluation of high-value agricultural produce with diverse water sources: Case study from Southern California. *Environmental Research Letters*, 13(2), 025007. <https://doi.org/10.1088/1748-9326/aaa49a>
- Bendotti Avocado. (2021). *Public disclosure statement: Joe Bendotti & Co. Product certification FY 2021–2022 projected*. https://www.climateactive.org.au/sites/default/files/2022-01/Joe%20Bendotti%20%26%20Co_Initial%20Cert_Year%201%20FY2021-22%20%28projected%29_PDS_0.pdf (Accessed 5 April 2023)
- Bessou, C., Basset-Mens, C., Tran, T., & Benoist, A. (2013). LCA applied to perennial cropping systems: A review focused on the farm stage. *The International Journal of Life Cycle Assessment*, 18(2), 340–361. <https://doi.org/10.1007/s11367-012-0502-z>
- Bessou, C., Basset-Mens, C., Latunussa, C., Vélú, A., Heitz, H., Vannière, H., & Caliman, J. P. (2016). Partial modelling of the perennial crop cycle misleads LCA results in two contrasted case studies. *The International Journal of Life Cycle Assessment*, 21(3), 297–310. <https://doi.org/10.1007/s11367-016-1030-z>
- Birkved, M., & Hauschild, M. Z. (2006). PestLCI – A model for estimating field emissions of pesticides in agricultural LCA. *Ecological Modelling*, 198(3–4), 433–451. <https://doi.org/10.1016/j.ecolmodel.2006.05.035>
- Bojacá, C. R., Wyckhuys, K. A. G., & Schrevens, E. (2014). Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. *Journal of Cleaner Production*, 69, 26–33. <https://doi.org/10.1016/j.jclepro.2014.01.078>
- Boulay, A. M., & Lenoir, L. (2020). Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations. *Ecological Indicators*, 111, 106017. <https://doi.org/10.1016/j.ecolind.2019.106017>

- Brentrup, F., Lammel, J., Stephani, T., & Christensen, B. (2018). Updated carbon footprint values for mineral fertilizer from different world regions. In *Proceedings of the 11th International Conference on Life Cycle Assessment of Food* (17–19 October). Bangkok, Thailand.
- Brito de Figueirêdo, M. C., Potting, J., Lopes Serrano, L. A., Bezerra, M. A., da Silva Barros, V., Gondim, R. S., & Nemecek, T. (2016). Environmental assessment of tropical perennial crops: The case of the Brazilian cashew. *Journal of Cleaner Production*, 112, 131–140. <https://doi.org/10.1016/j.jclepro.2015.05.134>
- Cambria, D., & Pierangeli, D. (2012). Application of a life cycle assessment to walnut tree (*Juglans regia* L.) high quality wood production: A case study in southern Italy. *Journal of Cleaner Production*, 23(1), 37–46. <https://doi.org/10.1016/j.jclepro.2011.10.031>
- Carbon Neutral Avocados. (2021). *Public disclosure statement: Carbon neutral avocados product certification 2021–2022 projected*. <https://www.ecoavo.com.au/certification> (Accessed 5 April 2023)
- Cerutti, A. K., Bruun, S., Beccaro, G. L., & Bounous, G. (2011). A review of studies applying environmental impact assessment methods on fruit production systems. *Journal of Environmental Management*, 92(10), 2277–2286. <https://doi.org/10.1016/j.jenvman.2011.04.018>
- Cerutti, A. K., Beccaro, G. L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., & Bounous, G. (2014). Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. *Journal of Cleaner Production*, 73, 125–135. <https://doi.org/10.1016/j.jclepro.2013.09.017>
- Coltro, L., and Karaski, T. U. (2019). Environmental indicators of banana production in Brazil: Cavendish and Prata varieties. *Journal of Cleaner Production* 207, 363–378. <https://doi.org/10.1016/j.jclepro.2018.09.258>
- Cucurachi, S., Scherer, L., Guinée, J., & Tukker, A. (2019). Life cycle assessment of food systems. *One Earth*, 1(3), 292–297. <https://doi.org/10.1016/j.oneear.2019.10.014>
- D'Abbadie, C., & Akbari, S. (2023). *WA Avocado Life Cycle Analysis (LCA)*. Department of Primary Industries and Regional Development. <https://www.agric.wa.gov.au/land-use/wa-avocado-life-cycle-analysis-lca> (Accessed 5 April 2023)
- DairyNZ. (2022). *DairyNZ annual report 2021/22*. https://www.dairynz.co.nz/media/5795962/dnz_annual_report_full_2022.pdf (Accessed 2 January 2023)

- Dicks, L. V., et al. (2019). What agricultural practices are most likely to deliver “sustainable intensification” in the UK? *Food and Energy Security*, 8(1), e00148.
<https://doi.org/10.1002/fes3.148>
- EPD International. (2019). *PCR Fruits and nuts. Product Category Classification UN CPC 013. 2019-01, Version 1.01. Valid until 21/01/2023*. (Version 1.01) [UN CPC 013]. Available for download at: <https://api.environdec.com/api/v1/EPDLibrary/Files/40cecf40-cb08-4a86-174e-08dc25c78130/Data> (Accessed 2 September 2020)
- EPD International. (2023). *Environmental performance indicators*.
<https://www.environdec.com/resources/indicators> (Accessed 15 January 2021)
- Esteve-Llorens, X., Ita-Nagy, D., Parodi, E., González-García, S., Moreira, M. T., Feijoo, G., & Vázquez-Rowe, I. (2022). Environmental footprint of critical agro-export products in the Peruvian hyper-arid coast: A case study for green asparagus and avocado. *Science of The Total Environment*, 818, 151686. <https://doi.org/10.1016/j.scitotenv.2021.151686>
- Fantke, P. (2019). Modelling the environmental impacts of pesticides in agriculture. In B. P. Weidema (Ed.), *Assessing the environmental impact of agriculture* (pp. 177–228). Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2018.0044.08>
- FAO, IFAD, UNICEF, WFP, & WHO. (2023). *The state of food security and nutrition in the world. Urbanization, agrifood systems transformation and healthy diets across the rural-urban continuum*. <https://doi.org/10.4060/cc3017en>
- FAO & WHO. (2019). *Sustainable healthy diets—Guiding principles*.
<https://www.who.int/publications/i/item/9789241516648> (Accessed 15 May 2023)
- Frankowska, A., Jeswani, H. K., & Azapagic, A. (2019). Life cycle environmental impacts of fruits consumption in the UK. *Journal of Environmental Management*, 248, 109111.
<https://doi.org/10.1016/j.jenvman.2019.06.012>
- Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J., & Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, 341(6141), 33–34. <https://doi.org/10.1126/science.1234485>
- Gentil, C., Basset-Mens, C., Manteaux, S., Mottes, C., Maillard, E., Biard, Y., & Fantke, P. (2020). Coupling pesticide emission and toxicity characterization models for LCA: Application to open-field tomato production in Martinique. *Journal of Cleaner Production*, 277, 124099.
<https://doi.org/10.1016/j.jclepro.2020.124099>

- Goossens, Y., Annaert, B., De Tavernier, J., Mathijs, E., Keulemans, W., & Geeraerd, A. (2017). Life cycle assessment (LCA) for apple orchard production systems including low and high productive years in conventional, integrated and organic farms. *Agricultural Systems*, 153, 81–93. <https://doi.org/10.1016/j.agsy.2017.01.007>
- Graefe, S., Tapasco, J., & Gonzalez, A. (2013). Resource use and GHG emissions of eight tropical fruit species cultivated in Colombia. *Fruits*, 68(4), 303–314. <https://doi.org/10.1051/fruits/2013075>
- Green, A., Nemecek, T., Smetana, S., & Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696. <https://doi.org/10.1016/j.jclepro.2021.127696>
- Hadjian, P., & Bahmer, T., & Egle, J. (2019). Life cycle assessment of three tropical fruits (avocado, banana, pineapple). https://www.blog.industrialecology.uni-freiburg.de/wp-content/uploads/2019/03/LCA_tropical_fruits_Julian_Egle_Tobias_Bahmer_Peiman_Hadjian.pdf (Accessed 14 May 2021)
- Hasler, K., Bröring, S., Omta, S. W. F., & Olfs, H. W. (2015). Life cycle assessment (LCA) of different fertilizer product types. *European Journal of Agronomy*, 69, 41–51. <https://doi.org/10.1016/j.eja.2015.06.001>
- Hauschild, M., Goedkoop, M., Guinee, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., De Schryver, A., Pennington, D., Pant, R., Sala, S., Brandao, M., & Wolf, M. (2011). *Recommendations for life cycle impact assessment in the European context—Based on existing environmental impact assessment models and factors (International Reference Life Cycle Data System—ILCD handbook)*. Luxembourg: Publications Office of the European Union; JRC61049.
- Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life cycle assessment: Theory and practice*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-56475-3>
- Herath, I. (2013). *The water footprint of agricultural products in New Zealand: The impact of primary production on water resources* [Doctoral dissertation, Massey University, New Zealand]. Massey Research Online <https://mro.massey.ac.nz/items/7213a0d2-6eaf-4717-b2ab-59acbce4c083>
- Herath, I., Green, S., Horne, D., Singh, R., McLaren, S., & Clothier, B. (2013). Water footprinting of agricultural products: Evaluation of different protocols using a case study of New Zealand

- wine. *Journal of Cleaner Production*, 44, 159–167.
<https://doi.org/10.1016/j.jclepro.2013.01.008>
- Hergoualc'h, K., Akiyama, H., Bernoux, M., Chirinda, N., del Prado, A., Kasimir, Å., MacDonald, J. D., Ogle, S. M., Regina, K., & van der Weerden, T. J. (2019). N₂O emissions from managed soils, and CO₂ emissions from lime and urea application—2019 Refinement to the 2006 IPCC Guidelines for greenhouse gas inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf
- Hietala, S., Usva, K., Vieraankivi, M. L. *et al.* Environmental sustainability of Finnish pork production: life cycle assessment of climate change and water scarcity impacts. *International Journal of Life Cycle Assessment* 29, 483–500. <https://doi.org/10.1007/s11367-023-02258-7>
- HLPE. (2017). *Nutrition and food systems: A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*.
<https://www.unscn.org/en/news-events/recent-news?idnews=1745> (Accessed 8 July 2023)
- HLPE. (2020). *Food security and nutrition: Building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*.
<https://uwaterloo.ca/scholar/sites/ca.scholar/files/jclapp/files/HLPE2020.pdf>
- Horticulture New Zealand & Plant & Food Research. (2018). *Fresh facts 2018*.
<https://unitedfresh.co.nz/technical-advisory-group/fresh-facts> (Accessed 17 March 2020)
- Horticulture New Zealand & Plant & Food Research. (2021). *Fresh facts 2021*.
<https://unitedfresh.co.nz/technical-advisory-group/fresh-facts> (Accessed 15 December 2022)
- Hume, A., Barber, A., East, A., McLaren, S., Deurer, M., Clothier, B., & Palmer, J. (2009). *Carbon footprinting for the apple supply chain – methodology and scoping study. Landcare Research Contract Report: LC0809/174*.
- Hume, A., Mithraratne, N., Sinclair, R. J., Snelling, C., Deurer, M., Barber, A., & East, A. (2010). Greenhouse gas footprinting and berryfruit production. Blackcurrants project summary. *Final report*. Available for download at:
https://www.academia.edu/9134960/Hume_A_Mithraratne_N_and_R_J_Sinclair_Greenhouse_gas_footprinting_and_berryfruit_production_Blackcurrent_project_summary_Landcare_Research_Report_for_Ministry_of_Agriculture_and_Forestry_New_Zealand_September_2010

- Iglesias, I., & Echeverria, G. (2022). Current situation, trends and challenges for efficient and sustainable peach production. *Scientia Horticulturae*, 296, 110899. <https://doi.org/10.1016/j.scienta.2022.110899>
- Jamie Gray. (2018). Booming horticulture exports forecast to soon rise to \$5.6b. *NZ Herald*. <https://www.nzherald.co.nz/business/booming-horticulture-exports-forecast-to-soon-rise-to-56b/CXSMN5LMBXHEK3GTGW4VUMZXB4/> (Accessed 3 July 2023)
- Jones, J., McLaren, S., & Chen, Q. (2020). Repurposing grape marc in Marlborough: The way forward. Available for download at: <https://www.marlboroughwinenz.com/winetimeline/grape-marc-study-repurposing-grape-marc-in-marlborough-the-way-forward-by-jim-jones-sarah-mclaren-and-qun-chen>
- Kaewmai, R., Grant, T., Mungkalasiri, J., & Musikavong, C. (2021). Assessing the water scarcity footprint of food crops by growing season available water remaining (AWARE) characterization factors in Thailand. *Science of the Total Environment* 763. <https://doi.org.ezproxy.massey.ac.nz/10.1016/j.scitotenv.2020.143000>
- Keyes, S., Tyedmers, P., & Beazley, K. (2015). Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. *Journal of Cleaner Production*, 104, 40–51. <https://doi.org/10.1016/j.jclepro.2015.05.037>
- Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., & Clark, S. (2014). Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. *Journal of Cleaner Production*, 73, 183–192. <https://doi.org/10.1016/j.jclepro.2013.09.057>
- Lazzerini, G., Lucchetti, S., & Nicese, F. P. (2014). Analysis of greenhouse gas emissions from ornamental plant production: A nursery level approach. *Urban Forestry & Urban Greening*, 13(3), 517–525. <https://doi.org/10.1016/j.ufug.2014.02.004>
- Ledgard, S., & Falconer, S. (2019). Update of the carbon footprint of fertilisers used in New Zealand. Available for access at: https://natlib.govt.nz/records/43119481?search%5Bh%5D%5Bdc_type%5D=Iwi%2FHapu+Authority&search%5Bi%5D%5Bcreator%5D=Fertiliser+Association+%28N.Z.%29&search%5Bpath%5D=items
- Li, C., Li, Y., Cui, D., Li, Y., Zou, G., Thompson, R., Wang, J., & Yang, J. (2022). Integrated crop-nitrogen management improves tomato yield and root architecture and minimizes soil residual N. *Agronomy*, 12(7), 7. <https://doi.org/10.3390/agronomy12071617>

- Life Cycle Initiative. (2023). *The USEtox Model / USEtox®*. <https://usetox.org/model> (Accessed 15 October 2021)
- Longo, S., Mistrett, M., Guarino, F., and Cellura, M. (2017). Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy. *Journal of Cleaner Production*, 140, 654-663. <http://dx.doi.org/10.1016/j.jclepro.2016.02.049>
- Lovatt, C. J. (2010). Alternate bearing of “Hass” avocado. *California Avocado Society 2010 Yearbook*, 93, 125–140.
- Majumdar, S., McLaren, S., Siebert, B., & Sorensen, S. (2022). Evaluating the environmental impacts of growing avocados in New Zealand. In *LCA Foods 2022 Book of Proceedings. 13th International Conference on Life Cycle Assessment of Food*. Lima, Peru.
- Martin-Gorriz, B., Gallego-Elvira, B., Martínez-Alvarez, V., & Maestre-Valero, J. F. (2020). Life cycle assessment of fruit and vegetable production in the Region of Murcia (south-east Spain) and evaluation of impact mitigation practices. *Journal of Cleaner Production*, 265, 121656. <https://doi.org/10.1016/j.jclepro.2020.121656>
- McAuliffe, G. A., Takahashi, T., Lee, M. R. F., Jebari, A., Cardenas, L., Kumar, A., Pereyra-Goday, F., Scalabrino, H., & Collins, A. L. (2023). A commentary on key methodological developments related to nutritional life cycle assessment (nLCA) generated throughout a 6-year strategic scientific programme. *Food and Energy Security*, 12, 1–6. <https://doi.org/10.1002/fes3.480>
- McLaren, S. J., Hume, A., & Mithraratne, N. (2010). Carbon management for the primary agricultural sector in New Zealand: Case studies for the pipfruit and kiwifruit industries. *7th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2010)*, 22–24 September 2010, Bari, Italy.
- McLaren, S., Clothier, B., Barber, A., McNally, S., Bullen, L., Mazzetto, A., & Ledgard, S. (2021). *Updating the carbon footprints for selected New Zealand agricultural products*. <https://www.mpi.govt.nz/dmsdocument/51079-Updating-the-carbon-footprint-for-selected-New-Zealand-agricultural-products-an-update-for-apples-kiwifruit-and-wine/>
- McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., De Camillis, C., Renouf, M., Rugani, B., Saarinen, M., van der Pols, J., Vázquez-Rowe, I., Vallejo, A. A., Bianchi, M., Chaudhary, A., Chen, C., Cooreman-Algoed, M., Dong, H., Grant, T., Green, A., Hallström, E., Hoang, H. M., Leip, A., Lynch, J., McAuliffe, G., Ridoutt, B., Saget, S., Scherer, L., Tuomisto, H., Tyedmers, P., & van Zanten, H. (2021). Integration of environment and nutrition in life cycle assessment of food items: Opportunities and challenges. <https://doi.org/10.4060/cb8054en>

- McNally, S., & Gentile, R. (2021). *Agricultural greenhouse gas emissions and carbon sequestration from a range of perennial horticultural crops in New Zealand*. Plant & Food Research. Milestone No. 89920. Contract No. 39301. Job code: P/443078/01. SPTS No. 21329.
- Meier, M. (2019). Using life cycle assessment to compare intensive versus extensive agricultural systems. In B. P. Weidema (Ed.), *Assessing the environmental impact of agriculture* (pp. 139–152). Burleigh Dodds Science Publishing.
- Milà i Canals, L. (2003). *Contributions to LCA methodology for agricultural systems. Site-dependency and soil degradation impact assessment* [Doctoral dissertation, Universitat Autònoma de Barcelona, Spain]
<https://investigacion.usc.gal/documentos/5d2bd89a29995218d8741a91>
- Milà i Canals, L., Burnip, G. M., & Cowell, S. J. (2006). Evaluation of the environmental impacts of apple production using life cycle assessment (LCA): Case study in New Zealand. *Agriculture, Ecosystems & Environment*, 114(2–4), 226–238. <https://doi.org/10.1016/j.agee.2005.10.023>
- Ministry for Primary Industries. (2018). *Situation and outlook for primary industries 2018*. Available for download at: <https://www.mpi.govt.nz/resources-and-forms/economic-intelligence/situation-and-outlook-for-primary-industries/sopi-reports/>
- Ministry for the Environment. (2020). *Measuring emissions: Detailed guide 2020*. Available for download at: <https://environment.govt.nz/publications/measuring-emissions-detailed-guide-2020/>
- Ministry for the Environment. (2021). *New Zealand's greenhouse gas inventory 1990–2019*. Available for download at: <https://environment.govt.nz/facts-and-science/climate-change/new-zealands-greenhouse-gas-inventory/previous-greenhouse-gas-inventories/>
- Mithraratne, N., Barber, A., & McLaren, S. J. (2010). *Carbon footprinting of the kiwifruit supply chain—Report on methodology and scoping study*.
https://www.landcareresearch.co.nz/assets/researchpubs/Kiwifruit_Methodology_Report_2010.pdf
- MPI. (2023). *Climate change and the primary industries / MPI - Ministry for Primary Industries*. <https://www.mpi.govt.nz/funding-rural-support/environment-and-natural-resources/climate-change-primary-industries/> (Accessed 25 April 2023)
- Müller, K., Holmes, A., & Deurer, M., Clothier, B. E. (2015). Eco-efficiency as a sustainability measure for kiwifruit production in New Zealand. *Journal of Cleaner Production*, 106, 333–342. <https://doi.org/10.1016/j.jclepro.2014.07.049>

- Nemecek, T., & Schnetzer, J. (2012). *Methods of assessment of direct field emissions for LCIs of agricultural production systems*. Agroscope Reckenholz-Tänikon Research Station ART & ecoinvent Centre. Available for download at: www.ecoinvent.org
- Nemecek, T., Bengoa, X., Lansche, J., Roesch, A., Faist-Emmenegger, M., Rossi, V., & Humbert, S. (2020). *Methodological guidelines for the life cycle inventory of agricultural products—World Food LCA Database*. https://simapro.com/wp-content/uploads/2020/11/WFLDB_MethodologicalGuidelines_v3.5.pdf
- Nicese, F. P., & Lazzerini, G. (2012). CO₂ sources and sinks in ornamental plant nurseries. *International Society for Horticultural Science*.
http://www.actahort.org/books/990/990_8.htm
- Notarnicola, B., Sala, S., Anton, A., McLaren, S. J., Saouter, E., & Sonesson, U. (2017). The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, 140, 399–409.
<https://doi.org/10.1016/j.jclepro.2016.06.071>
- NZ Avocado. (2018). *Situational analysis and five-year plan*. Available for download at: <https://industry.nzavocado.co.nz/download/situational-analysis-and-five-year-plan-grower-roadshow-presentation-april-2024/>
- NZ Avocado. (2020). *NZ Avocado annual report 2020*. Available for download at: <https://industry.nzavocado.co.nz/download/annual-report-2020/>
- NZ Avocado. (2021). *NZ Avocado annual report 2021*. Available for download at: <https://industry.nzavocado.co.nz/download/annual-report-2021/>
- NZ Avocado. (2022). *Annual report 2022*. Available for download at: <https://industry.nzavocado.co.nz/download/nz-avocado-annual-report-2022/>
- NZ Avocado. (2023). *Sustainability*. <https://industry.nzavocado.co.nz/research/sustainability/> (Accessed 5 July 2023)
- NZ HEA. (2017). *New Zealand Horticulture Export Authority Annual Report 2017*. Available for download at: <https://hea.co.nz/2012-05-11-03-06-16/hea-annual-reports>
- NZ Wine. (2022). *New Zealand Winegrowers sustainability report 2022*.
<https://www.nzwine.com/media/22253/nz-winegrowers-sustainability-report-2022.pdf>

- O'Dwyer, J., Walshe, D., & Byrne, K. A. (2018). Wood waste decomposition in landfills: An assessment of current knowledge and implications for emissions reporting. *Waste Management*, 73, 181–188. <https://doi.org/10.1016/j.wasman.2017.12.002>
- Payen, S., & Ledgard, S. F. (2017). Aquatic eutrophication indicators in LCA: Methodological challenges illustrated using a case study in New Zealand. *Journal of Cleaner Production*, 168, 1463–1472. <https://doi.org/10.1016/j.jclepro.2017.09.064>
- Payen, S., Falconer, S., & Ledgard, S. F. (2018). Water scarcity footprint of dairy milk production in New Zealand – A comparison of methods and spatio-temporal resolution. *Science of the Total Environment* 639, 504-515. <https://doi-org.ezproxy.massey.ac.nz/10.1016/j.scitotenv.2018.05.125>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. <https://doi.org/10.1126/science.aag0216>
- Renaud-Gentié, C., Dijkman, T. J., Bjorn, A., & Birkved, M. (2014). Modeling pesticides emissions for Grapevine Life Cycle Assessment: Adaptation of Pest-LCI model to viticulture. In R. Schenck & D. Huizenga (Eds.), *Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector* (pp. 1075–1085). ACLCA.
- Robertson, K., Garnham, M., & Symes, W. (2014). Life cycle carbon footprint of the packaging and transport of New Zealand kiwifruit. *The International Journal of Life Cycle Assessment*, 19(10), 1693–1704. <https://doi.org/10.1007/s11367-014-0775-5>
- Rosenbaum, R. K., et al. (2015). The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA. *The International Journal of Life Cycle Assessment*, 20(6), 765–776. <https://doi.org/10.1007/s11367-015-0871-1>
- Rosenstock, T. S., Rosa, U. A., Plant, R. E., & Brown, P. H. (2010). A reevaluation of alternate bearing in pistachio. *Scientia Horticulturae*, 124(2), 149–152. <https://doi.org/10.1016/j.scienta.2009.12.007>
- Sharma, N., Singh, S. K., Mahato, A. K., Ravishankar, H., Dubey, A. K., & Singh, N. K. (2019). Physiological and molecular basis of alternate bearing in perennial fruit crops. *Scientia Horticulturae*, 243, 214–225. <https://doi.org/10.1016/j.scienta.2018.08.021>
- Solarte-Toro, J. C., Ortiz-Sanchez, M., & Cardona Alzate, C. A. (2022). Environmental life cycle assessment (E-LCA) and social impact assessment (SIA) of small-scale biorefineries implemented in rural zones: The avocado (*Persea Americana* var. *Americana*) case in

- Colombia. *Environmental Science and Pollution Research*, 30(4), 8790–8808.
<https://doi.org/10.1007/s11356-022-20857-z>
- Stoessel, F., Juraske, R., Pfister, S., & Hellweg, S. (2012). Life cycle inventory and carbon and water foodprint of fruits and vegetables: Application to a Swiss retailer. *Environmental Science & Technology*, 46(6), 3253–3262. <https://doi.org/10.1021/es2030577>
- Svanes, E., & Johnsen, F. M. (2019). Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. *Journal of Cleaner Production*, 238, 117773.
<https://doi.org/10.1016/j.jclepro.2019.117773>
- The Beehive. (2018). Growing a sustainable and productive primary sector.
<https://www.beehive.govt.nz/release/growing-sustainable-and-productive-primary-sector>
 (Accessed 1 July 2023)
- United Nations Department of Economic and Social Affairs. (2015). *Transforming our world: The 2030 agenda for sustainable development (A/RES/70/1)*.
<https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981> (Accessed 1 July 2023)
- Vatsanidou, A., Fountas, S., Liakos, V., Nanos, G., & Katsoulas, N., Gemtos, T. (2020). Life cycle assessment of variable rate fertilizer application in a pear orchard. *Sustainability*, 12(17), 6893. <https://doi.org/10.3390/su12176893>
- Vinyes, E., Gasol, C. M., Asin, L., Alegre, S., & Muñoz, P. (2015). Life cycle assessment of multiyear peach production. *Journal of Cleaner Production*, 104, 68–79.
<https://doi.org/10.1016/j.jclepro.2015.05.041>
- Vinyes, E., Asin, L., Alegre, S., Muñoz, P., Boschmonart, J., & Gasol, C. M. (2017). Life cycle assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. *Journal of Cleaner Production*, 149, 313–320.
<https://doi.org/10.1016/j.jclepro.2017.02.102>
- Winstone Wallboards. (2023). Gypsum GIB. <https://www.gib.co.nz/products/gypsum/gypsum/>
 (Accessed 24 May 2021)
- World Benchmarking Alliance. (2022). *2021 food and agriculture benchmark—Insights report*.
<https://assets.worldbenchmarkingalliance.org/app/uploads/2022/03/2021-Food-and-Agriculture-Benchmark-Insights-Report.pdf>

- Wu, P., Feng, Y., Pienaar, J., & Xia, B. (2015). A review of benchmarking in carbon labelling schemes for building materials. *Journal of Cleaner Production*, 109, 108–117.
<https://doi.org/10.1016/j.jclepro.2015.07.067>
- Yan, M., Cheng, K., Yue, Q., Yan, Y., Rees, R. M., & Pan, G. (2016). Farm and product carbon footprints of China's fruit production—Life cycle inventory of representative orchards of five major fruits. *Environmental Science and Pollution Research International*, 23(5), 4681–4691.
<https://doi.org/10.1007/s11356-015-5670-5>
- Yan, X., Ye, D., Tang, Y., Muneer, M. A., Christie, P., Tou, C., Xu, W., Shen, B., Xu, J., and Zhang, J. (2023). Potential mitigation of environmental impacts of intensive plum production in southeast China with maintenance of high yields: Evaluation using life cycle assessment. *Frontiers in Plant Science* 14. <https://doi.org/10.3389/fpls.2023.1158591>
- Zespri. (2022). *Zespri annual report 2021/22*. Available for download at:
<https://www.zespri.com/en-NZ/publications/annualreports>

Chapter 4 Life cycle-based environmental indicators in agri-food Voluntary Sustainability Standards: case study of New Zealand avocado post-harvest activities

This chapter builds on the work in Chapter 3, by extending the system boundaries of New Zealand produced avocados to include downstream life cycle stages as well. The following sections are being drafted for journal submission.

4.1 Introduction

Environmental Life Cycle Assessment (LCA) is a well-established holistic tool to quantify the environmental impacts of product systems, processes, and/or activities from cradle to grave, i.e. across the life cycle (ISO, 2006). It is primarily a decision-support tool (Pryshlakivsky & Searcy, 2021; Wenzel, 1998), and application areas include hotspot analysis across sectors and contexts (e.g. Barthel et al., 2017; Castellani et al., 2017; Cornago et al., 2022; Kanafani et al., 2021; Lavers Westin et al., 2019; Sonnemann & Margni, 2015), benchmark development (e.g. Cossu et al., 2023; Dias et al., 2017; Paratscha et al., 2019), establishment of performance indicators (e.g. Ghadimi et al., 2019; Repar et al., 2017), eco-design (e.g. Bianco et al., 2021; McAloone & Pigosso, 2018; Tao et al., 2018), and policy/legislation development (e.g. Castellani et al., 2017; European Commission et al., 2021; Hélias et al., 2022). However, there are relatively few studies that investigate use of LCA in sustainability certification and labelling schemes²⁵, and existing studies have mostly focused on non-agri-food products in the context of ISO type 1 ecolabel criteria (e.g. Baldo et al., 2002; Clift, 1993; Milà i Canals et al., 2002; Neitzel, 1997). In this paper, we investigate the extent to which LCA is currently used (or not) to develop indicators for agri-food environmental sustainability certification schemes (also known as Voluntary Sustainability

²⁵ Most studies on agri-food sustainability standards and certification schemes have focused on how these labels influence consumer decisions and consumer perceptions about them and their effectiveness (Brach et al., 2018; Goossens et al., 2017; Kühne et al., 2023; Potter et al., 2021; Williams et al., 2023).

Standards or VSS) and investigate the options for adoption of LCA-based indicators using a case study of the New Zealand avocado sector.

This paper introduces VSS and reviews their use of LCA indicators in Section 4.2. Sections 4.3 and 4.4 report on an LCA of the post-harvest stages of the New Zealand avocado sector which is assessed alongside an existing LCA of avocado cultivation in New Zealand. Section 4.5 reflects on the main insights from this LCA study and their implications in the context of developing life cycle-based indicators for a sector-wide VSS for New Zealand avocados, as well as in the wider context of agri-food VSS in other sectors. Conclusions are provided in Section 4.6.

4.2 Agri-food VSS addressing environmental sustainability

4.2.1 Overview of agri-food VSS addressing environmental sustainability

VSS are defined as *‘standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics, including respect for basic human rights, worker health and safety, the environmental impacts of production, community relations, land use planning and others’* (UNFSS, 2012). The number of agri-food VSS has been growing since the 1990s and they have especially proliferated in the last decade (Tayleur et al., 2018; UNFSS et al., 2020). In a recent analysis on the state of global agri-food VSS, Kemper et al. (2024) considered 11 mainstream VSS for 8 major commodity crops. The report notes that 9% of the global harvested area of these 8 commodity crops had VSS certification, and the total certified area grew from 2.5 million hectares in 2008 to almost 23 million hectares globally in 2022 (Kemper et al., 2024). VSS are therefore becoming more significant as market-driven instruments to facilitate sustainability across global value chains (Marx et al., 2022; Traldi, 2021; UNCTAD, 2021).

A literature search was conducted to identify the mainstream third-party certified (TPC)²⁶ VSS addressing environmental sustainability, defined as those whose uptake has been sufficiently

²⁶ VSS certification is the result of a successfully conducted verification process such as an audit. When this audit is conducted by a third-party intermediary, it is known as Third-Party Certification (TPC) (Hatanaka et al., 2005).

extensive that they have become research subjects in academic literature. First a search was conducted on Scopus and Google Scholar using the search terms '(agri-food) OR (agrifood) OR (agricultur*) OR (horticultur*) OR (food)' AND '(Voluntary Sustainability Standard*) OR (VSS) OR (ecolabel*)'. Results were limited to the years 2000-2024, and to English language sources. This search resulted in 468 results. These included articles evaluating certification as a governance tool (Auld, 2010; Cashore et al., 2004; van der Ven & Barmes, 2023; Vince & Haward, 2019), the VSS landscape (Kemper et al., 2024; Tallontire et al., 2012; Tayleur et al., 2017), research trends in VSS (Marx et al., 2022), VSS coverage and outcomes (Dietz & Grabs, 2022; Traldi, 2021), and several focused studies on individual VSS like Global G.A.P., Fairtrade, and Rainforest Alliance (Agni Kalfagianni & Doris Fuchs, 2011; Akrong et al., 2022; Bellamy et al., 2016; Gather & Wollni, 2022; Meemken, 2020). They also included sector-specific studies and associated VSS including those for forestry (Cashore et al., 2005; Zanchini et al., 2022), seafood (Bush et al., 2013; Oosterveer, 2019; Osmundsen et al., 2020), cacao (Parra-Paitan et al., 2023; Villacis et al., 2022), and coffee (Canwat, 2023; Dietz et al., 2021; Vanderhaegen et al., 2018). The search results were then narrowed down to exclude more generic studies (e.g. use of certification for global environmental governance) and focus on those which addressed agri-food VSS by name and addressed them specifically, either individually or in multi-VSS comparative studies. This enabled compilation of a preliminary list of mainstream agri-food VSS. Most of these studies focused only on a few VSS like Global G.A.P., Rainforest Alliance, Fairtrade, RSPO, and organic certifications. Next, the ITC Standards Map (ITC, 2023) was reviewed to check for any additional third-party certified VSS omitted in the original search, and additional ones were added to the list. In a third step, a separate search was conducted for each VSS in the compiled list, to identify any additional missing literature on the preliminary list of agri-food

Certification can also be 'first-party' (when it is based on internal corporate standards and driven by a motivation to self-regulate) or second-party (verification by industry association or consumer groups which have a 'user interest' in the product). However, TPC-certified VSS are considered the most credible due to the auditing and verification process (Brach et al., 2018; Darnall et al., 2018). Therefore, this research only considered TPC VSS.

VSS. Table 4.1 provides the final list of mainstream third-party certified agri-food and forestry VSS based on this process.

Table 4.1 Mainstream VSS examples with relevant product sectors they cover (Source: individual standard websites and ITC Standards Map, 2023)

Food Category	Sectoral Application	Name of VSS	Geographic Scope*	Identified in literature search	Listed in ITC Standards Map database
Horticulture	Sugarcane, sugar, ethanol	Bonsucro	International	✓	
	Cotton	Better Cotton Initiative (BCI) Cotton Made in Africa (CMiA)	International Regional	✓ ✓	
	Oil Palm	Roundtable on Sustainable Palm Oil	International	✓	
	Coffee	The Common Code for the Coffee Community – 4C	International	✓	
	Soy	Roundtable on Responsible Soy (RTRS)	International	✓	
	Multiple	Rainforest Alliance Fairtrade Proterra	International International International	✓ ✓ ✓	
Aquaculture/ Fisheries	Seafood	Marine Stewardship Council (MSC) Aquaculture Stewardship Council (ASC) Global Seafood Alliance Best Aquaculture Practices (BAP)	International International International	✓ ✓	✓
		Friend of the Sea marine aquaculture	International		✓
Viticulture	Grape and wine	Sustainable Winegrowing New Zealand (SWNZ) California Sustainable Winegrowing Alliance (CSWA) Equalitas V.I.V.A. Sustainable Wine South Africa (uses the Integrated Production of Wine (IPW) South	National (New Zealand) Regional (California) National (Italy) National (Italy) National (South Africa) National (Australia)	✓ ✓ ✓ ✓ ✓ ✓	

		Africa standard) Sustainable Winegrowing Australia (uses the Australian Wine Industry Standards of Sustainable Practice for Viticulture and Winery)			
Others	Multiple sectors (Dairy/meat/poultry/fl oriculture/arable crops)	Red Tractor LEAF Marque Sustainable Rice Platform Unilever Sustainable Agriculture Code Origin Green Global G.A.P Country-level G.A.P. schemes (e.g. PhilGAP, ThaiGAP) Food Alliance African Organisation for Standardisation (ARSO) Protected Harvest	National (U.K.) International International International National (Ireland) International National (multiple) National (USA) Regional (Africa) National (USA)	✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓
Others	Multiple sectors (Dairy/meat/poultry/fl oriculture/arable crops) (Organic)	IFOAM Organics USDA Organic Biogro NZ Pacific organic aquaculture Naturland organic aquaculture National Programme for Organic Production (NPOP)	International International (USDA) National (New Zealand) Regional (Pacific countries) International National (India)	✓ ✓ ✓ ✓	✓ ✓

4.2.2 Types of environmental indicators in agri-food VSS

Sustainability indicators used in agri-food VSS are typically categorised as practice-, target-, and performance-based (FAO, 2014). Practice-based indicators, also known as process- or technology-based indicators are checkbox-type and prescriptive in nature requiring yes/no answers (e.g. *'Organic waste material should be composted and used for soil conditioning'*). Target-based indicators require that certain management plans be put into place, with associated targets that must be achieved over a stipulated period of time (e.g. *'A documented plan on identifying opportunities to improve energy efficiency shall be available, multi-year if necessary'*). Performance-based indicators on the other hand, are verifiable metrics (e.g. *'Report % farm area under natural vegetation cover'* or *'Report water use for irrigation in total and per unit of product (L, L/kg)'*). Such metric-based indicators of farm-level sustainability performance can facilitate and provide evidence of continuous improvement (Freidberg, 2017; Hatanaka et al., 2022; Konefal et al., 2022; Merli et al., 2018; Veale et al., 2015; Viart & Rein, 2013). While practice- and target-based indicators can also support continuous improvement, a performance-based metric like 'quantity of fertiliser used per hectare' or 'eutrophication potential per kg fruit', provides an actual measurable baseline which can then be improved upon. This facilitates continuous improvement rather than 'box ticking', which over time can become merely a compliance exercise. Performance-based metrics can be input-based (e.g. quantity of water applied per kg fruit) or outcome-based (e.g. climate change impact per kg fruit). Of the few examples of performance-based indicators in agri-food VSS (see Appendix A, Table A1), most are input-based or monitoring metrics, and only a few assess environmental outcomes. In general, the vast majority of VSS indicators are practice- and target-based (Bush et al., 2013; Hatanaka et al., 2022; Konefal et al., 2022; McGarr-O'Brien et al., 2023; Veale et al., 2015).

4.2.3 Use of LCA-based indicators in agri-food VSS

Table 4.2 lists the agri-food VSS from Table 4.1 that have at least one LCA-based indicator.

Table 4.2 Agri-food VSS with LCA-based indicators in their criteria

Name of VSS	LCA-based indicator	Methodology followed	Life cycle stages addressed*	LCIA-based benchmark in indicator	Literature discussing use of LCA in VSS
Bonsucro	CF	PAS 2050:2008	Farm Mill	Threshold/peer/individual	South Pole (2020) Viart et al. (2016)
Origin Green	CF	PAS 2050:2008 ISO 14067:2018	Farm/orchard	Peer/Individual	-
Roundtable on Sustainable Palm Oil (RSPO)	CF	ISO 14040:2006 ISO 14044:2006	Plantation	Individual	Amri et al. (2023) Bessou (2016) Bessou et al. (2012, 2014) South Pole (2020)
Aquaculture Stewardship Council (ASC)	CF	GHG protocol corporate standard or ISO14040/14044	Farm	Individual	-
Valutazione dell’Impatto della Vitivinicoltura sull’Ambiente (V.I.V.A.)	CF WF	ISO 14067:2018 ISO 14044:2006 Water Footprint Network Method (Hoekstra et al., 2011)	Vineyard Winery Distribution End-of-life	Individual	D’Ammaro et al. (2021) Merli et al. (2018) Casolani & Liberatore (2024) Casolani et al. (2023)
Equalitas	CF WF	ISO 14064-1:2019 ISO 14067:2018 ISO 14046:2014	Vineyard Winery	Individual	Casolani et al. (2023) Galletto & Barisan (2019)

* Includes upstream and downstream processes involved in the included life cycle stage (e.g., production and transport of fertilisers). CF: carbon footprint; WF: water footprint.

It can be seen most of the LCA-based indicators only assess the growing/farm stage of the life cycle (the exceptions are V.I.V.A and Equalitas which also include the winery stage, and Bonsucro which includes the milling stage for sugar and ethanol). They generally exclude the upstream (nursery and planting in the case of horticultural products) and post-harvest (packing, distribution, retail, transport, and consumption) stages. However, some horticultural LCA studies include the nursery stage (Basset-Mens et al., 2016; Bessou et al., 2013, 2016; Cambria & Pierangeli, 2012; Cerutti et al., 2014; Lazzerini et al., 2014; Nicese & Lazzerini, 2013). With respect to the post-harvest stages, Li et al. (2022) calculated that almost 20% of total food system-related GHG emissions can be attributed to food transport. Further, Crippa et al. (2021) noted that packaging accounted for 5.4% of the total GHG emissions from global food systems in 2015. Food loss and waste (FLW) is also an issue of global concern; approximately 14% of food is lost from the post-harvest stage onwards in a food product's supply chain, and an additional 17% food wastage is attributed to the retail and consumption stages (FAO, 2019; United Nations, 2023).

Table 4.2 also shows that the indicators are almost entirely focused on carbon footprints (CFs). Only two VSS (V.I.V.A. and Equalitas) have an LCA-based criterion for water use in addition to a CF. V.I.V.A requires a water footprint (WF) (aligned to the guidelines of the Water Footprint Network) to be conducted across the wine growing and winery activities, whereas Equalitas requires a WF to be carried out for the wine growing and bottling stages based on the ISO 14046:2014 standard.

With respect to the CF indicators, some of the standards use their own bespoke CF calculators (e.g. the Bonsucro calculator, Origin Green's Carbon Navigator, and RSPO's Palm GHG calculator). In viticulture, Spain's V.I.V.A. and Equalitas also require the CF to be calculated using designated, industry-specific calculators (Merli et al., 2018). These bespoke CF calculators are aligned with international standards like PAS 2050:2008, ISO 14067:2018, ISO 14040:2006, and/or ISO 14044:2006. Other VSS like Rainforest Alliance and Red Tractor recommend that growers use

UK's Cool Farm Tool (which follows the GHG Protocol Accounting and Reporting standard for calculating Scope 1,2, and 3 emissions). When using the Cool Farm Tool, growers are encouraged to calculate all three scope emissions but are permitted to exclude Scope 3 emissions. The ASC feed standard and two ASC sectoral schemes (flatfish and salmon) also require the GHG Protocol standard to be followed (including Scope 3 emissions). LEAF Marque requires CFs to be calculated, but mainly for on-farm emissions. Also, the choice of tool is left to the grower and so the CF methodology may or may not be LCA-based and/or aligned with international CF standards.

Most of the LCA-based metrics used in agri-food VSS also incorporate benchmarking. Benchmarking is the process of comparing an entity's products, services, processes, and performance against a reference value and is now widely acknowledged as facilitating continuous performance improvement across industries and sectors, including agriculture (Gasso et al., 2025). Galindro et al. (2019) characterise benchmarking into two main categories: internal benchmarking within an organisation, and benchmarking against the performance of an external entity. ISEAL Alliance (2020) outlines four types of benchmarking processes in the context of VSS: 1) threshold benchmark, i.e. the absolute benchmark which an entity needs to meet to obtain certification; 2) ranking benchmarks in which entities are scored against performance topics and then ranked against each other; 3) peer comparison (not ranking) relative to similar entities (the same as external benchmarking); and 4) setting a benchmark as a future target that an entity must work towards. In addition, benchmarks may also be used to assess an entity's own performance over time. The performance indicators in five of the six VSS in Table 4.2 are used to assess and communicate information about performance relative to previous years for an individual entity, or in the case of Origin Green and Bonsucro, relative to the performance of other entities in the sector (as the sector average). Bonsucro is the only VSS that uses LCIA values as thresholds as well to be met in its environmental criteria (Veale et al., 2015). It sets carbon footprint thresholds (calculated using the Bonsucro calculator) for the production of sugarcane (<40 kg CO₂ eq./t cane), sugar <0.4 kg CO₂ eq./t sugar), and ethanol

(<24 g CO₂ eq./MJ fuel)(Bonsucro, 2023; Viart et al., 2016). In addition, the new ASC farm standard which is currently undergoing public consultation and will be fully operational in 2027, combines all the sectoral standards into one (ASC, 2025). It requires farmers to have a GHG management plan, in which it defines sector-specific GHG values as upper threshold benchmarks. Once operational, farmers will be expected to take actions to keep their emissions under the threshold and continuously improve on them year on year.

4.2.4 Research on use of LCA in agri-food VSS

With regards to research on how LCA is used to develop indicators in current agri-food VSS, 11 studies were identified which referred to the use of LCA in CF calculators. Of these, several offered only a cursory reference to the CF tool with regards to the FU, life cycle stages, alignment with international standards, and/or main sources of emissions (Amri et al., 2023; Casolani et al., 2023; Casolani & Liberatore, 2024; Galletto & Barisan, 2019; Merli et al., 2018; Viart et al., 2016). Five studies considered the CF tool methodology in more detail. For example, while acknowledging the strength of the Bonsucro standard due to its LCA-based threshold benchmarks, South Pole (2020) noted that the GHG tool methodology required improvements. They suggested that the standard currently uses emission factors from different sources and should transition to using ecoinvent factors for all emissions. Moreover, they suggested that aerial spraying and worker transport be included, and the allocation method be changed from energy to economic, to accurately reflect market realities. They also recommended that indirect land use change be included as an impact category, and that updated FAO values be used for direct land use change.

Bessou et al. (2014, 2016) provided the scientific basis of the (then) newly developed PalmGHG calculator, including aspects such as land use change (land clearing, fertiliser production and transport, field emissions (direct and indirect emissions from N₂O and CO₂ from urea application and fuel), mill emissions (CH₄ from palm oil mill effluent also known as POME, and fuel), and cultivation of peat soils which result in the release of CO₂ and N₂O. The studies also

included the use of biogenic carbon as well as details about the carbon stocks for different land uses included in the calculator. A pilot study conducted in 2011 using the PalmGHG calculator was detailed in Bessou et al. (2014). The data was collected by nine RSPO certified mills in Indonesia, Malaysia, Papua New Guinea, and Brazil and resulted in highly variable impact values ranging from -0.02 to +8.32 t CO₂ eq./t crude palm oil (CPO). The main hotspots were land clearing, peat cultivation, fertiliser manufacture and use, and CH₄ emissions from POME. While these studies were published a decade ago, the main emission sources of palm oil production (as calculated using the PalmGHG calculator) remain unchanged as noted in a more recent study, especially the significance of peat and land conversion in terms of contribution to overall GHG emissions (Amri et al., 2023).

In their benchmarking study of Italian wine CFs, D'Ammaro et al. (2021) studied the CFs of 33 V.I.V.A. certified wines, and in the methods section, they outlined the main points of the V.I.V.A. framework underlying the CF calculation. These include scope (FU – 0.75 L bottle of wine, and main inputs at each life cycle stage from vineyard to consumption), allocation rules (96% to grape and 4% to grapemarc), product transport details (mode of transport, utilisation ratio, distance), pallet composition and reuse, waste management (transport to recycling , incineration, and landfill), land use change occurring in the last 20 years), and inclusion of biogenic carbon. The study found that producing a bottle of wine generated a CF of 0.81-1.84 kg CO₂ eq./bottle across its life cycle. The packing and cellar phases were the biggest contributors to impacts along the life cycle, accounting for 40% and 27% of total emissions respectively, with glass bottle manufacturing contributing to most of the packaging impacts. These results were in line with another study on V.I.V.A. certified wines in Italy (Casolani et al., 2023), other wine supply chain LCA studies, and olive oil manufacturing studies as well (Accorsi et al., 2015; Ferrara & De Feo, 2018). This shows that, although most VSS only focus on the growing stage, downstream stages can be significant contributors to an agri-food product system along its life cycle.

Only three studies were found that looked at using LCA to develop agri-food VSS/ecolabel indicators: shrimp aquaculture in Thailand, sheep milk in New Zealand, and sheep milk cheese in Italy. Mungkung et al. (2006) conducted an LCA study of the shrimp aquaculture product system in Thailand to investigate how LCA can be used to determine the impact and life cycle stage hotspots for development of criteria for a potential ecolabelling scheme. This study followed ISO type 1 ecolabel criteria development processes and did not discuss how impact values could be used as performance metrics in VSS criteria. Moreover, the study included multiple impact categories and assessed the entire life cycle of the product from cradle to grave. However, it found that the downstream life cycle stage impacts were negligible compared with the production of shrimp and concluded that three environmental aspects were relevant for ecolabelling criteria for the Thai shrimp sector: electricity and fossil fuel use, eutrophication caused by nutrient loading, and the use of burnt lime to address soil and water acidity in the ponds. Mohan (2018) used a cradle-to-farm gate LCA to inform the development of key criteria for a potential farm-based environmental certification scheme for sheep milk in New Zealand; however, these criteria were practice-based and did not include data or performance-based indicators as benchmarks. In one recent study, Cossu et al. (2023) attempted to demonstrate how the Made Green in Italy scheme could be potentially applied to hard sheep milk cheese using LCA-based impact values as benchmarks. This was the only study which investigated the use of LCIA-based values as thresholds in the VSS criteria. It considered multiple impact categories and took a cradle-to-grave approach for developing threshold benchmarks. It did not, however, develop individual thresholds for different impact categories. Instead, this study used normalisation and weighting to arrive at a single score to develop ranges of performance classes into which products could potentially be categorised²⁷. The uncertainty and value judgements

²⁷ The label can be hypothetically awarded to the products in the best performance class, and the benchmark performance class (provided the latter demonstrate a commitment to continuous improvement). The products scoring below the benchmark will not be awarded the certification.

associated with these steps remain a challenge as they can significantly impact the final results of the study (Hélias & Servien, 2021; Pizzol et al., 2017).

4.2.5 Summary

The review identified there are relatively few existing agri-food VSS that use LCA-based indicators, and that that these schemes overwhelmingly focus on just the CF and just the agricultural stage in the life cycle of agri-food products. The LCA data is used in these schemes to develop benchmarks mainly for comparison with external entities in the industry sector, except for Bonsucro which is the only operational scheme with threshold benchmarks that must be met to achieve certification (plus the new ASC standard due to become operational in 2025). There is therefore a need to develop a better understanding about the use of LCA-based indicators in agri-food supply chains. This paper uses a case study of the New Zealand avocado sector, extending a previous LCA of New Zealand avocado orchards (Majumdar & McLaren, 2023) to include the post-harvest packing and distribution life cycle stages, in order to investigate these topics.

4.3 Case study of the New Zealand avocado sector

4.3.1 Goal and scope

This current paper extends the system boundaries of the previous orchard-level study (Majumdar & McLaren, 2023) to include the post-harvest transport and packing stage, as well as distribution to the first Points of Sale (PoS) in domestic and export markets. Table 4.3 provides details about the eight scenarios that are modelled (see Section 4.3.2 for more details, and Appendix D, Tables D8-D30 for routes and calculation methods for distances). The functional unit (FU) for this study was 1 kg Hass avocados produced and packaged in New Zealand and distributed to domestic and international destinations.

Table 4.3 Supply chain scenarios for packing and distribution to local and export markets

Scenario Name	Destination	Mode of Transport	Type of Packaging*
ScA (Aus, Ship)	Australia	Truck (163 km), rail (5 km), ship (2,922 km)	SLT
ScB (Aus, Air)	Australia	Truck (286 km), air (2,293 km)	SLT
ScC (SK, Ship)	South Korea (Busan)	Truck (126 km), ship (11,775 km)	SLT
ScD (SK, Air)	South Korea (Incheon)	Truck (230 km), air (9620 km)	SLT
ScE (North, BLF)	North Island	Truck (238 km)	BLF
ScF (North, PC)	North Island	Truck (238 km)	PCs
ScG (South, BLF)	South Island	Truck (1,117 km), ferry (100 km)	BLF
ScH (South, PC)	South Island	Truck (1,117 km), ferry (100 km)	PCs

** Single Layered Trays (SLTs) for export; Bulk Loose Fill (BLF) and Plastic Crates (PCs) for domestic distribution*

The study excluded all elementary flows to and from the system that contributed to 1% or less of the final result for any one of the studied impact categories (following EPD International (2019) guidelines). Therefore, port operations in New Zealand were not considered because they were assumed to have negligible impacts (port operations accounted for 1% of total climate change impact in the study by Mithraratne et al., 2010). Also, as per EPD International (2019), business travel activities related to the packing stage were excluded; however, a sensitivity analysis was conducted to determine its contribution to overall impacts.

The majority of the avocados grown in New Zealand are exported to Australia by sea, and South Korea was the second largest export market for New Zealand-grown avocados during the data collection period. Communication with industry representatives revealed that market diversification strategies were being followed by the sector, with increasing exports to Asian markets, and planned exports to North America and Canada (Pers Comm., AVOCO, 2023). Therefore, impacts were also modelled to additional export destinations in Asia and USA. In addition, onward transport to the RDC and supermarkets in Australia were modelled in another scenario to determine the influence of these additional downstream stages on supply chain impacts.

Primary data was used all foreground processes, while secondary data (ecoinvent datasets) were used for background processes (e.g. extraction of raw materials and production/transport of fuel and refrigerants). With respect to temporal representativeness, packhouse and distribution data was collected for the period 1 June 2019 to 31 May 2020; this was most representative of harvesting and packing timelines in New Zealand. The impact categories used in the previous orchard-level study by Majumdar and McLaren (2023) were identified in an earlier materiality assessment undertaken by NZ Avocado (climate change, eutrophication, water use, freshwater ecotoxicity, and terrestrial ecotoxicity). To facilitate comparison with the orchard stage, the same impact categories were considered in this study as well.

4.3.2 Modelling activities and scenarios

4.3.2.1 Packing stage

Data were collected from two packhouses that are based in the Bay of Plenty (see Appendix D for questionnaire sent to packhouses) and collectively deliver 27% to the total avocado packing activity in New Zealand (NZ Avocado, Pers. Comm., 5 April 2022). All activities for the post-harvest transport and packing activities (hereafter referred to as the packing stage) are listed in Table 4.4, and relevant input data are provided in Appendix D, Tables D2-D8.

Table 4.4 Activities and inputs in the packing stage

Sub-Stage	Inputs
Avocados delivered to packhouse (transport of avocados from orchard to packhouse)	• Wooden bins • Transport by truck
Waterblasting and sanitising fruit	• Sanitiser • Fresh water • Electricity associated with town supply of water • LPG for avocado dryers
Sorting, grading, packing, and washing bins and packlines ('packline sub-stage')	• Electricity • Fresh water • Electricity associated with town supply of water • Packaging material (plastic for stickers, strapping and EAN labels; paper backing for EAN labels; wooden pallets; cardboard packaging including boxes, trays, pocket packs, corner boards,

	corrucups; quicklime, and disinfectant) • Fuel used to transport these packaging materials to the packhouse
Cooling and storage ('coolstore sub-stage')	• Refrigerant (including fuel to transport it to the packhouse) • Electricity
Post-packing transport and waste management	• Additional production of the packaging wasted during the packing process (since it is sent back to recycling) • Truck transport of waste packaging to recycling centre

On the packline, the sanitised avocados are digitally and manually sorted, graded, and packed into the three categories (Class 1, Class 2, and Class 3). Usually, Class 1 fruit are almost entirely packaged for the export market and are usually packed into cardboard Single Layer Trays (SLTs) with cardboard pocket packs. Class 2 and 3 fruit are for the domestic market and are usually bulk packed or loose filled into cardboard boxes without pocket packs (commonly referred to as BLF packaging) or packed in plastic crates (PCs). Ungraded fruit is processed into cold-pressed avocado oil, and a small portion of the total avocados sent to the packhouse are rejected and returned to growers as stock feed. No reject fruit is sent to landfill as waste.

Following the EPD International (2019) guidelines, impacts were allocated by mass across the three different fruit grades. The fruit sent for processing into avocado oil was partitioned from the system after sorting at the packline sub-stage. Less than 1% of total avocados were rejected and sent as feed for livestock; they were also partitioned from the system after sorting. For the small quantity of waste packaging materials, transport to the recycling centre was included (following the 'simple cut-off' method recommended in the International EPD System, PAS 2050, and the Greenhouse Gas Protocol (British Standards Institution (BSI), 2011, Annex D, pg 31; EPD International, 2019, Section 4.6.2, pg 10; WRI & WBCSD, 2011, Section 9.3.6, pg 73).

4.3.2.2 Distribution stage

After the avocados are packed, the pallets are loaded into refrigerated containers, which are then transported by truck to ports/airports for export, or distribution/retail centres for domestic sale.

Export markets

Export data were collected from AVOCO (see Appendix D for questionnaire sent to the exporter), the largest avocado exporter in New Zealand which has over 65% of the export market share for New Zealand-produced avocados (AVOCO, Pers. Comm., June 2021). The AVOCO data (volumes in Tray Equivalents (TEs)²⁸ and distances in km) were used to calculate a weighted average distance for transport from packhouse to New Zealand ports (road and in some cases, rail) and airports (road only) for exports to Australia and South Korea respectively. Transport volumes and quantities were calculated using the packaging quantities and their TEs, while weighted averages were calculated for all transport modes and distances. Ship transport to Australia was modelled to three ports in Australia (Sydney, Melbourne, and Brisbane) and their weighted average was used for ScA (sea freight to Australia). The avocados were transported to four destination airports: Brisbane, Melbourne, and Sydney in Australia, and Incheon in South Korea.

Domestic markets

AVOCO also markets avocados domestically. Their share in the avocado distribution to domestic markets is around 45% (AVOCO, Pers. Comm., May 2022)²⁹. Avocados for the domestic market were transported to nine drop-off points in the North and South Islands. Transport by road and

²⁸ A TE is a standard measure of avocado quantities in New Zealand determined for levy purposes and equals 5.5 kg of fruit.

²⁹ While AVOCO's export market share is large and representative of avocado export operations, their share in the domestic market is smaller. However, data about other domestic distributors and their market share in New Zealand was unavailable at the time of data collection.

ferry (between Wellington and Picton) was modelled for fruit using transport data for six packhouses provided by AVOCO. For distribution to the North Island, the weighted average for road transport to nine drop-off points in the North Island was modelled for avocados packaged in BLF boxes and PCs. The same method was followed for distribution to three drop-off points in the South Island, with the additional distance covered by the ferry trip between the North and South Islands.

4.4 Results

4.4.1 Results for the avocado supply chain

The post-harvest stages contribute an average of 41% of total supply chain impacts up to the overseas port for exports, and 22% of impacts to RDC for domestic supply respectively (Figure 4.1). Overall, the post-harvest stages contribute an average of 32% of the impacts across all the scenarios and impact categories, although contributions vary widely between 92% (climate change contribution for ScD (SK, Air)) and just 3% (freshwater ecotoxicity contribution for ScF (North, PC)). The average contribution of the post-harvest stages to total water use and terrestrial ecotoxicity values is also notable (41% and 38% respectively).

The post-harvest stages comprise packing and distribution activities. These activities contribute 46% and 54% respectively to the post-harvest impacts across the scenarios and impact categories.

For **international distribution**, airfreighting has a big influence on the results. The ScD (SK, Air) scenario has the longest airfreighting distance, and its distribution stage contributes more than 70% of the total post-harvest results in all impact categories except water use where it is 30%. For **domestic distribution**, transporting fruit to the South Island contributes an average 53% to the post-harvest impacts across all impact categories. This is twice the contribution when transporting to the North Island (27%) and is due to the differences in trucking distances.

The **packing** stage particularly contributes to post-harvest impacts for water use and freshwater ecotoxicity. Indeed, packing contributes >90% of the water use post-harvest impacts in all scenarios except ScD (SK,Air), and >50% of the freshwater ecotoxicity impacts in most scenarios (Figure 4.1). With respect to the types of packaging, SLT (used exclusively for export fruit) has the largest packing stage impacts, followed by the two domestic packaging types (BLF and PCs) (Figure 4.2). The packline sub-stage contributes the most to the packing stage when using SLTs and BLFs in most impact categories. When using PCs, the coolstore sub-stage is the major contributor to the packing stage impacts in most impact categories. When using SLTs and BLFs, the majority of the packline sub-stage impacts are from cardboard manufacturing. When using PCs, the majority of the packline and coolstore sub-stage impacts can be attributed to electricity use.

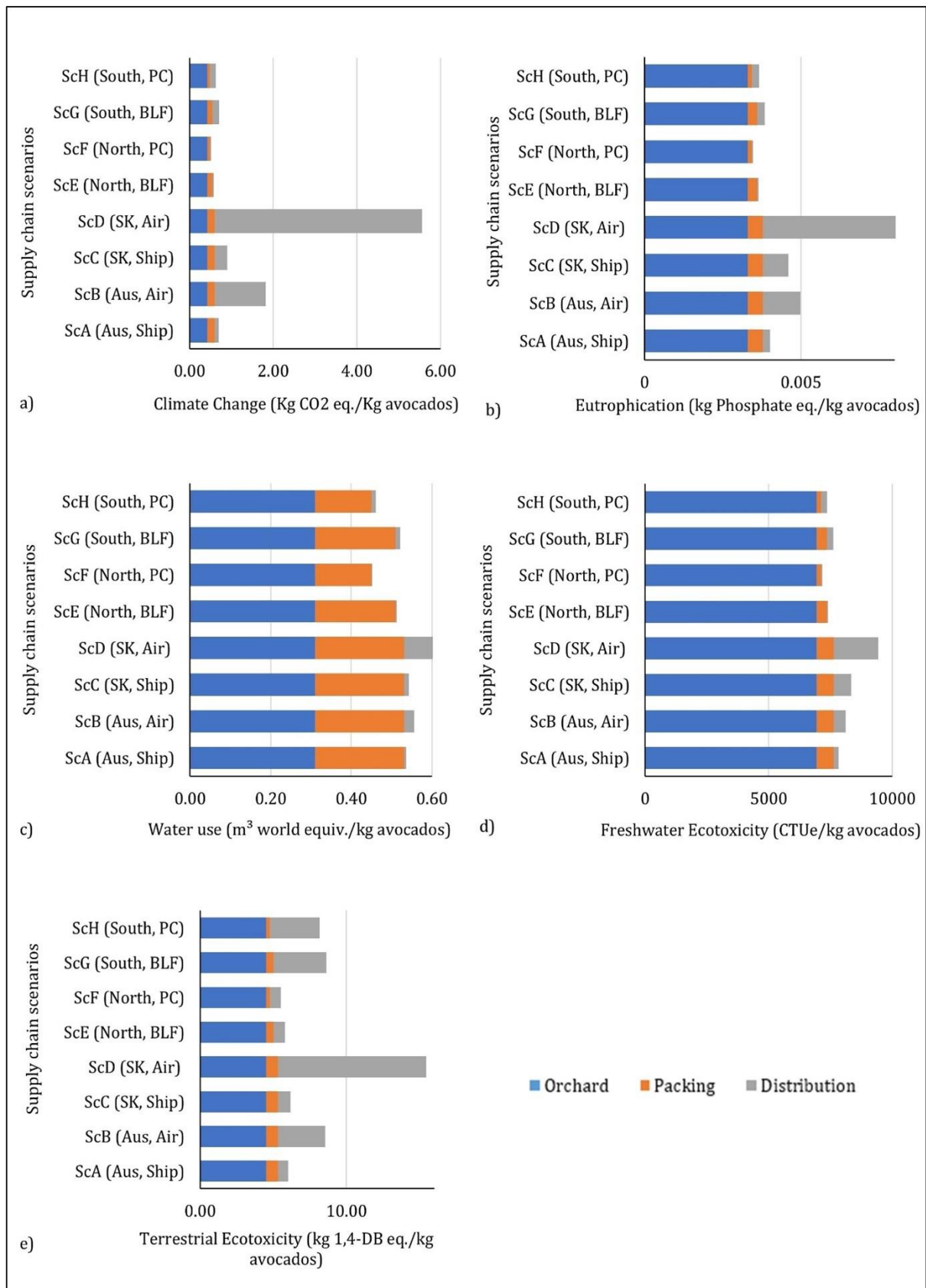


Figure 4.1 LCA scenario results for the orchard, packaging and distribution life cycle stages for a) climate change, b) eutrophication, c) water use, d) freshwater ecotoxicity, and e) terrestrial ecotoxicity

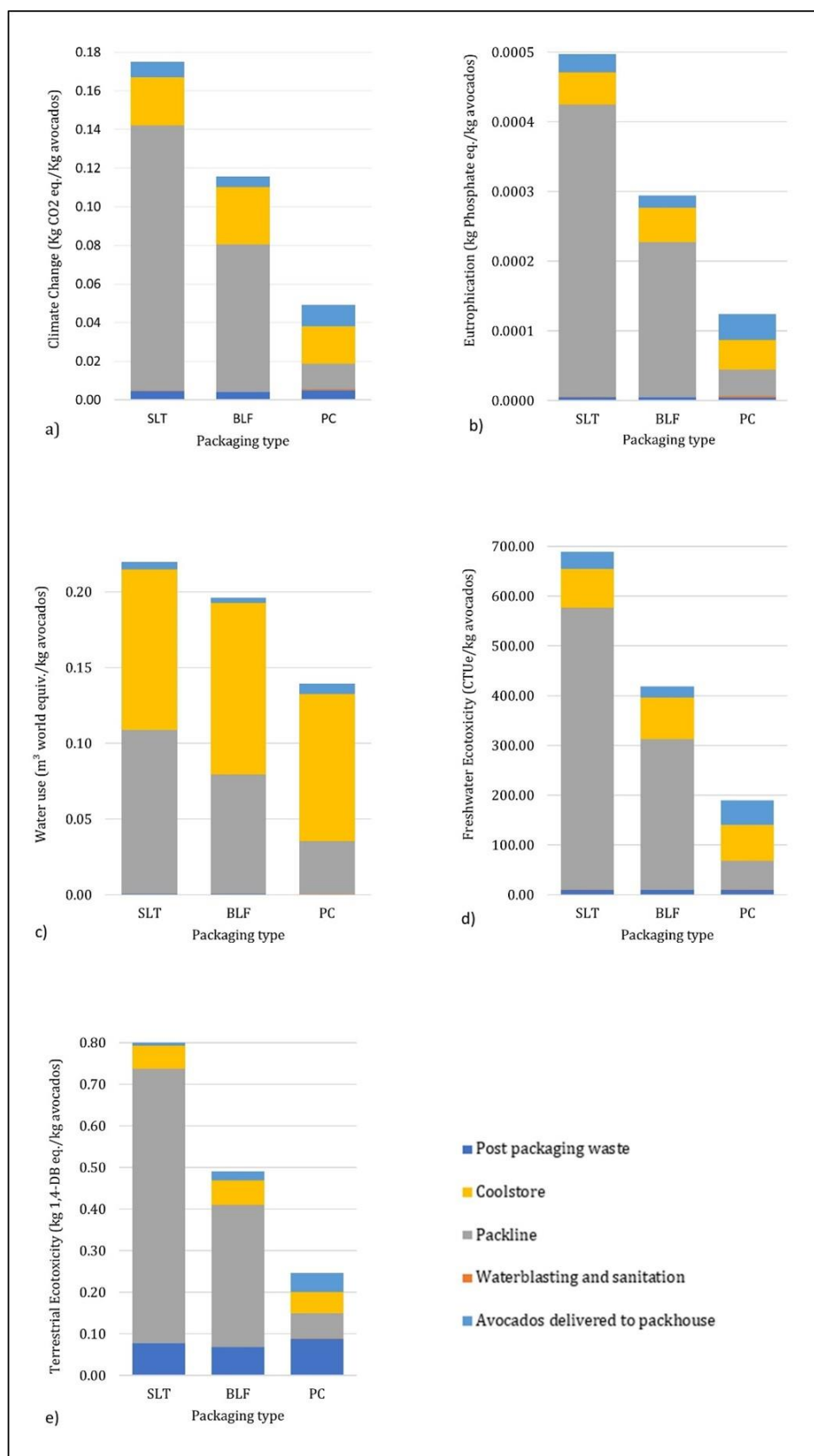


Figure 4.2 LCA results for the avocado packing stage extending from avocados arriving at packhouse through to leaving the coolstore for onward distribution. Results are shown for different packaging types – single layer tray (SLT), bulk loose fill (BLF), and plastic crates (PCs) for a) climate change, b) eutrophication, c) water use, d) freshwater ecotoxicity, e) terrestrial ecotoxicity.

4.4.2 Additional analysis for post-harvest stages

4.4.2.1 Inclusion of business transport

While the use of on-site forklift trucks and other equipment for moving produce, packaging, etc. is included in the packing stage in some LCA studies, the use of vehicles for business purposes (e.g. visits to growers, administering industry-wide initiatives like agrichemical programmes, other personnel travel, etc.) is usually excluded. To determine whether the inclusion of business travel influences the overall results in this study, data on fuel use for business travel were collected from the two packhouses. The increase in overall life cycle results was marginal (<2%) when either value was used (Appendix D, figure D1).

4.4.2.2 Export to alternative markets

Australia has traditionally been a significant export market for New Zealand grown and packaged avocados, with smaller quantities of fruit going to Asia (mainly South Korea, Japan, Singapore and Thailand). In recent years, avocados are additionally being exported to other Asian countries like Taiwan, China, India, Vietnam, and Hong Kong. Exporters have also begun trial shipments to USA by sea, and by ship and airfreight to Canada, and they foresee that these volumes will increase considerably in the coming years as exports to Australia steadily decline (pers. comm., AVOCO, 1 May, 2025). Post-harvest impacts for distribution to these additional destinations were modelled, using airfreight and shipping distances provided by AVOCO, and compared with the Australian and South Korean scenario results (Figure 4.3). Figure 4.3 shows that the results for the different additional export destinations are quite similar for shipping; airfreighting values are also similar, but differ more than shipping). This is because the distances to these additional export destinations range between 9,700-11,900 by sea (except for the east coast of USA which is 15,660 km away) and 7,600-9,600 km by sea and air respectively, and the results are proportional to these distances. However, the average airfreighting impacts across scenarios for each impact category are up to 10 times larger than the associated shipping values, the smallest difference being noted for water use and largest for climate change.

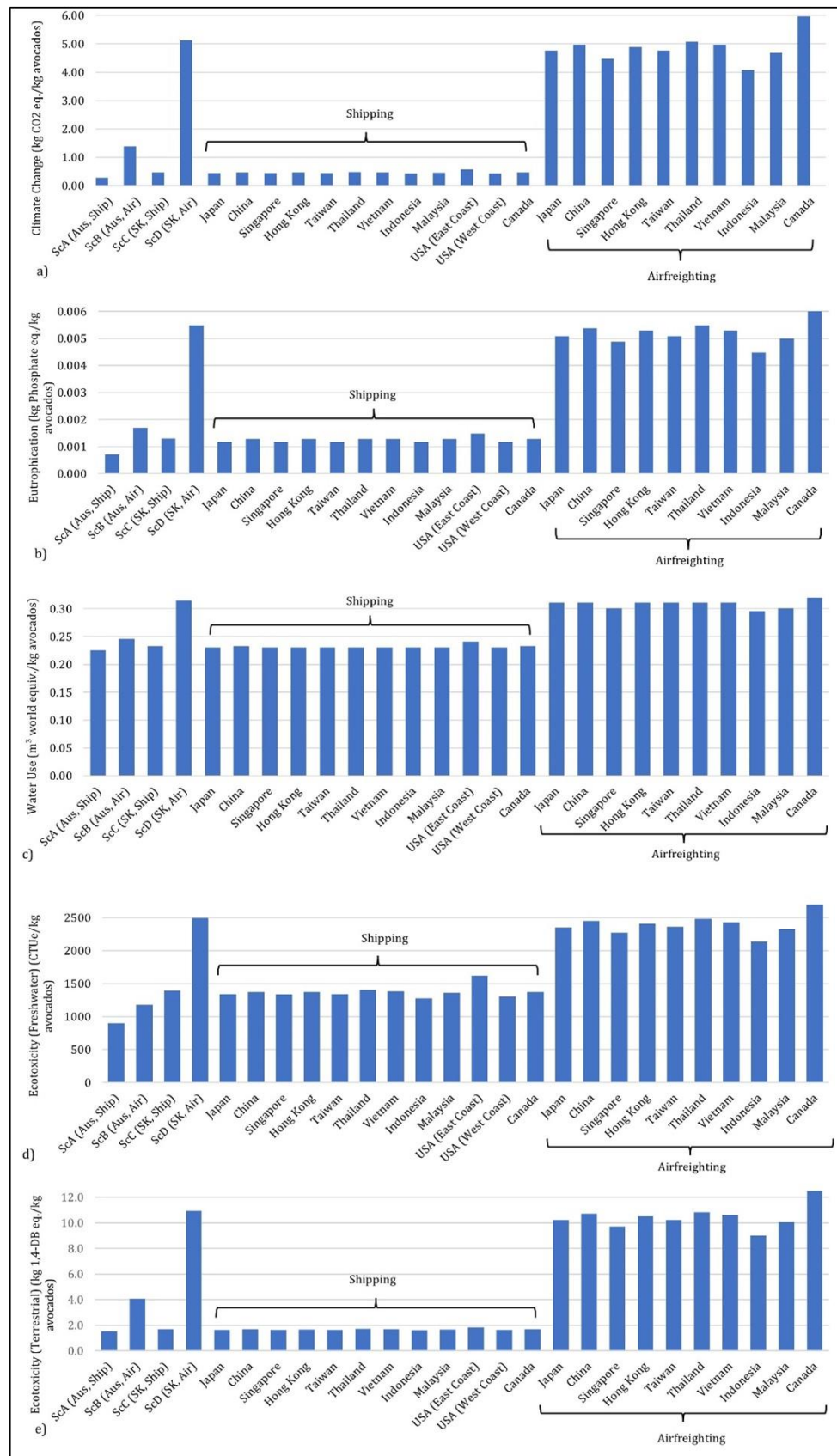


Figure 4.3 Post-harvest LCA results for distribution to diverse market destinations via shipping and airfreighting for a) climate change, b) eutrophication, c) water use, d) freshwater ecotoxicity, e) terrestrial ecotoxicity

4.4.2.3 Extending the system boundary

Figure 4.1 shows impacts up to the port in the destination country. However, activities after arrival at the port can also have substantial impacts (Dijkman et al., 2018; Iriarte et al., 2014; Tubiello et al., 2022). Therefore, in this additional analysis, the system boundary for ScA (Aus, Ship) was extended to include 5% fruit loss at the destination port³⁰, ripening the fruit in Australian ripening chambers³¹ at the port, transporting the fruit from the port to the RDC, and then on to the supermarket (using data provided by AVOCO). ScA (Aus, Ship) was chosen for comparison because it is the most common route and mode of transport for export avocados from New Zealand.

Figure 4.4 shows that extending the system boundary to the supermarket is associated with an increase of 4%, 12%, 21%, 37%, and 59% for water use, freshwater ecotoxicity, eutrophication, climate change, and terrestrial ecotoxicity respectively. The relative contributions of the three modelled post-port activities (ripening chambers, transport from port to RDC, transport from RDC to supermarket) vary across the impact categories, although the transport from the overseas port to RDC is always a minor contributor. The contribution of the ripening chamber is due to the Australian electricity grid mix which includes substantial generation from fossil fuels.

³⁰ There is little or no packaging waste at port as repackaging is done in existing boxes.

³¹ Some 'climateric' fruits like bananas, avocados, guavas, and papayas continue to ripen post-harvest unlike non-climateric ones like berries, citrus and watermelons (Indian Ministry of Agriculture, 2011). Climateric fruits are therefore harvested while still green and unripe so that they can endure the rigours of long-distance travel without becoming too ripe or rotting. However, supermarket customers demand ripe fruit and therefore climacteric fruits have to be subjected to induced ripening within temperature-controlled chambers.

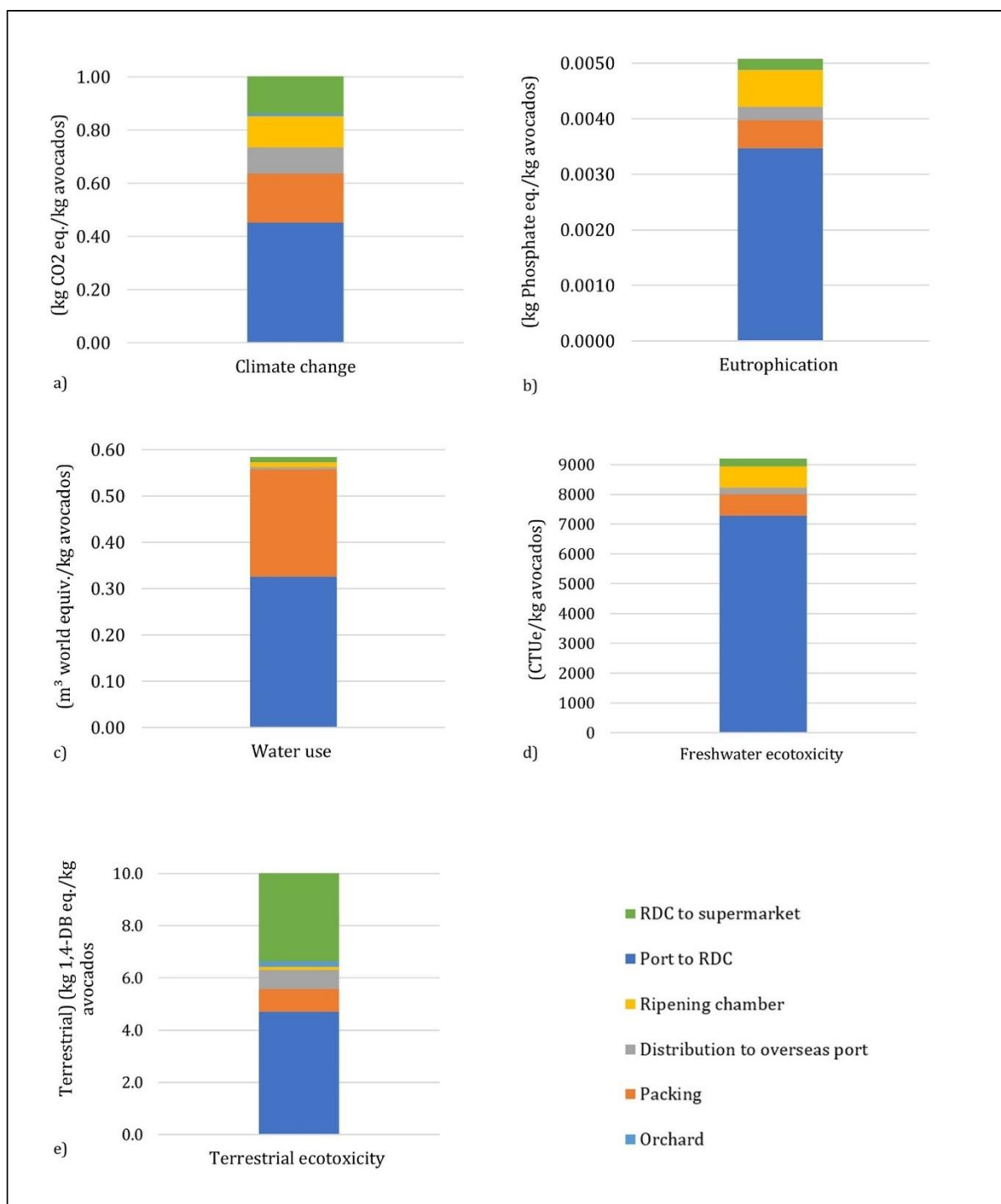


Figure 4.4 LCA results for ScA (Aus, Ship) scenario with system boundary extended to Australian supermarket for a) climate change, b) eutrophication, c) water use, d) freshwater ecotoxicity, e) terrestrial ecotoxicity

4.5 Discussion

4.5.1 Use of LCA indicators in a sector-based VSS: insights for the New Zealand avocado sector

4.5.1.1 Significance of post-harvest contributions to avocado life cycle

The post-harvest stages account for an average of 41% and 22% of total supply chain impacts up to the destination port for exports, and RDC for domestic supply respectively (see Figure 4.1). A similar relative contribution has been noted in other studies; for example, 35% of the climate change impacts for global agri-food systems in 2019 was attributed to non-farm stages such as packing, distribution, retail, and consumption (Tubiello et al., 2022). Several horticultural case studies have also shown similar findings (e.g. Basset-Mens et al., 2019; Frankowska et al., 2019; Kamalakkannan et al., 2022; Mithraratne et al., 2010; Payen et al., 2015; Pedreschi et al., 2022; Schwarz et al., 2016; Stoessel et al., 2012). The results of this study are thus aligned with existing literature and suggest that downstream stages should be included in whole-of-life assessments for avocados.

Implication for VSS in New Zealand avocado sector

As the orchard stage is generally the environmental hotspot in the New Zealand avocado supply chain, the orchard stage should be a focus for the development of an orchard VSS whose purpose is to drive environmental improvements in New Zealand avocado cultivation (Majumdar & McLaren, 2023). At the same time, this study shows that the post-harvest stages also have notable contributions to the total supply chain impacts in the same impact categories as assessed for the orchard stage. Therefore, these post-harvest activities should be included in an expanded sector-wide VSS that is oriented towards demonstrating the environmental credentials of the New Zealand avocado sector in both domestic and international markets.

4.5.1.2 Mode of transport

Distance has been a focal point in the 'food miles' and 'local food' debates (McLaren, 2009; Li et al., 2022; Petruzzelli et al., 2023; Solarz et al., 2023). To a certain extent, the findings of this

study align with this perspective, at least when comparing impacts based on the same mode of transport. For example, shipping to Australia has smaller post-harvest impacts than shipping to South Korea. Similarly, domestic transport to the South Island has larger post-harvests impact than to the North Island (when using the same kind of packaging) for all impact categories.

However, the mode of transport is a more significant determinant when comparing the supply chains on the basis of both distance and mode. For the different export destinations, airfreighting (ScB and ScD) always had higher post-harvest impacts than shipping across all impact categories (Figure 4.1). The alternative export market scenario analysis also showed the same. Airfreighting impacts were 43-1361% higher on average than shipping within each impact category for the additional export scenarios (Figure 4.3). Thus, airfreighting as a mode of transport is a major environmental hotspot in the New Zealand avocado sector for export markets. This finding aligns with published studies of intercontinental airfreighting of seafood³² (Winther et al., 2020; Ziegler et al., 2022; Ziegler & Hilborn, 2023), vegetables (Basset-Mens et al., 2019; Milà I Canals et al., 2008; Sim et al., 2007; Stoessel et al., 2012), and fruits (Michalský & Hooda, 2015; Stoessel et al., 2012). Indeed, efforts are increasingly underway by retailers to reduce their reliance on airfreight for food transport and in some cases, phase it out entirely (Gowans, 2023; Stoessel et al., 2012; Wagenvoort, 2022). In a global trade context, though, airfreight accounts for a very small percentage of total global food transport (<0.2%), with most international food transport occurring by sea (Ritchie & Roser, 2024), and this is the case for the New Zealand avocado sector as well.

The results also show that transport to the South Island of New Zealand has higher impacts than shipping to Australia in all impact categories (Figure 4.1). Particularly for terrestrial ecotoxicity, distribution-related impacts when transporting to the South Island are up to four times higher

³² A recent study on the New Zealand King Salmon life cycle found a 138% increase in air transport-related GHG emissions compared with sea transport (thinkstep ANZ, 2023).

than shipping to both Australia and South Korea. Similar results regarding the improved environmental performance of shipping compared with long-distance road haulage have been noted in other studies (e.g. Boschiero et al., 2019; Frankowska et al., 2019; Keyes, 2013; Nahlik et al., 2016; Pedreschi et al., 2022; Stoessel et al., 2012).

Implication for VSS in New Zealand avocado sector

Given the significant contribution of airfreighting to the total impacts when it is used in international distribution, a future sector-wide VSS should highlight this aspect. A simple non-LCIA-based indicator could be used such as, 'Quantity of fruit transported by air'.

For supply chains using ships and trucks, indicators should be developed primarily based on weighted emission factors (for example, per t.km). This will drive improvements in transport modes in the shorter term, e.g. use of slow steaming ships and electric or hybrid trucks. In addition, performance indicators based on actual distances (per kg avocados distributed) should also be developed for longer-term strategic decision-making about future markets. These recommendations are related to the distinction between operational and strategic decisions. VSS are oriented more towards operational decisions rather than longer-term strategic ones. This is why mode of transport is highlighted as a determinant in this section rather than distance – the latter would be related to choice of markets which is more of a strategic decision. Therefore, indicators are suggested accordingly, e.g. to facilitate moving away from air freighting to more efficient other forms of transport.

4.5.1.3 Packaging type

SLTs have the highest, and the PCs have the lowest, impacts across all impact categories (Figure 4.2). It is important to note, however, that in this study, the PCs were 'leased' from logistics providers and reused multiple times over their life cycle – therefore their production and end-of-life treatment was excluded from the study.

The packline sub-stage is the environmental hotspot for SLTs and BLFs, with most of the impacts attributed to the production of corrugated board for cardboard packaging – this has been noted

in other studies as well (Albrecht et al., 2013; Lo-Iacono-Ferreira et al., 2020). When using PCs, however, the coolstore is the major contributor to the packing stage impacts, followed by the packline (except terrestrial ecotoxicity, in which transport of avocados to the packhouse contributes the most), and electricity use is the main contributor to these coolstore and packline impacts. Other studies have shown that the coolstore sub-stage can be a big contributor to the packing stage impacts when fruit are stored for several months (e.g. Boschiero et al., 2019; Figueiredo et al., 2013; Mithraratne et al., 2010). But in the case of New Zealand avocados, their comparatively short shelf life requires them to be shipped shortly after harvesting. Therefore, they are usually kept in coolstores for only for 3-4 days, and so the coolstore makes only a minor contribution to the packing stage results with the exception of PCs where they are used multiple times and so the packaging has a small impact.

Implication for VSS in New Zealand avocado sector

The packaging results show a marked difference between impacts for the three different packaging types (SLTs, BLTs and PCs) (Figure 4.2). However, BLTs and PCs cannot be used for exported fruit, whereas they can be used interchangeably for domestic distribution. Therefore, two separate indicators should be defined for a sector-wide VSS depending upon whether the fruit is exported or distributed domestically:

- Exported fruit packaging indicators: the impacts associated with the SLT based on data collected from packhouses (per 1 kg avocado).
- Domestic fruit packaging indicators: the weighted average of the impacts from PCs and BLTs based on data collected from packhouses (per 1 kg avocado).

Either one or both of these indicators should be used depending upon the export/domestic orientation of the VSS.

4.5.1.4 Inclusion of business transport

The results of the additional scenario on business transport show that including these activities only marginally increases the impacts (up to 2%) (Appendix D, figure D1). Thus, business

transport related to packhouse activities is not significant in the context of whole supply chain impacts and can be omitted from such analyses. This aligns with the guidelines in the EPD International (2019) PCR document which states that business travel by personnel is not to be included when developing an EPD.

Implication for VSS in New Zealand avocado sector

Business transport can be omitted when developing indicators for a sector-wide VSS.

4.5.1.5 Importance of post-port activities in Australia

The study modelled post-port activities in Australia (using ScA as the baseline) as this is currently the main export market for New Zealand avocados. When extending the system boundary to include ripening chambers, and transport to the supermarket, the supply chain impacts increase considerably (up to 59%) across impact categories (Figure 4.4). Therefore, including distribution-related activities beyond the destination port is important to understanding the total supply chain impacts. The main activity hotspots in this extended supply chain scenario analysis are electricity use in the ripening chambers and fuel use for road transport. LCA studies usually omit the ripening stage due to lack of data (for example, Iriarte et al., 2014); only one study (Svanes & Aronsson, 2013) was found that included the ripening stage for banana exports and it used an electricity use value of 0.06 kWh/kg of bananas. The current study used a higher value of 0.11 kWh/kg avocados obtained from industry sources and therefore provides a more conservative impact result.

The increase in supply chain impacts due to the 5% fruit loss at the Australian port is marginal compared with the other post-port impacts, therefore FLW is not a hotspot in the New Zealand avocado supply chain up to the retail outlet. Other studies have emphasised the importance of FLW along the supply chain, but this is more often noted at the retail and consumption stages (Dijkman et al., 2018; Ingwersen, 2012; Kamalakkannan et al., 2022; Mithraratne et al., 2010; Svanes & Aronsson, 2013; Vinyes et al., 2017).

Implication for VSS in New Zealand avocado sector

The results showed that post-overseas port activities can make a notable contribution to the supply chain impacts and therefore these stages and the associated impacts should be included in supply chain analyses. However, in the context of VSS indicator development this can be a significant challenge due to inclusion of life cycle stages that are beyond the operational control of primary stakeholders (Ridoutt et al., 2016). In the case of the New Zealand avocado sector, growers, packers, and distributors have a certain degree of influence on the supply chain up to the destination port but not beyond it. Therefore, although this study shows the relevance of post-destination port life cycle stages from an environmental perspective, in the context of developing a sector-wide VSS the indicators should be limited to life cycle stages up to the destination port³³.

4.5.1.6 Benchmarking

As noted in Section 4.2.3, benchmarking is an important aspect of agri-food VSS to support continuous improvement via measurable metrics. The avocado case study showed that LCA-based indicator with associated benchmarks can be developed for sector-based VSS; however, they should be nuanced and context-specific. For example, the study showed that one single packing stage benchmark indicator is not appropriate for all supply chains – they need to be distinct for domestic and export distribution (Section 4.5.1.3). Similarly, with respect to modes of transport, airfreighting was the most significant determining factor for impacts associated with distribution to overseas markets, and so should be separately represented in VSS. For example, two separate indicators could be developed: for airfreighted and non-airfreighted

³³ In future versions of a VSS, however, if and when collaborations with post-port stakeholders like retailers and distributors are possible, then the benchmarks can be adjusted to include these stages. Indeed, including these stages could catalyse environmental improvements like, for example, using intermodal transport that allows for greater rail use, using low-emission trucks for road transport, and installing solar-powered ripening chambers as demonstrated recently by Australian retailer Coles (Matich, 2020).

distribution of fruit. The former could measure the quantity of fruit transported per year by air, with the national average quantity of airfreighted fruit used as the benchmark. The second indicator could measure the impact of transport per t.km per kg fruit; the national weighted average impact could be used as the benchmark. Total transport distance as a benchmark should be used only if transport distances increase significantly from current markets due to changing market dynamics.

Implication for VSS in New Zealand avocado sector

As long as the indicators are appropriately nuanced, the associated LCIA result values can serve as benchmarks for the New Zealand avocado sector. The exception to this is the recommendation for a non-LCIA based performance benchmark to address the occasional airfreighting of fruit to export destinations (Section 4.5.1.2). The benchmarks can be used for peer comparison or as thresholds – the decision would rest with the stakeholders who develop and operate the scheme. With respect to the *type of benchmark*, Bonsucro's threshold indicators are considered superior to the others (in terms of driving change) as they are more stringent (Section 4.2.3). Threshold benchmarks (determining award of certification) can thus be more effective at driving change in the post-harvest stages of the New Zealand avocado sector as well. However, as most VSS use benchmarks for peer comparison, values below the threshold could also be used for peer comparison within the avocado sector to drive continuous improvement.

4.5.2 Use of LCA indicators in a sector-based VSS: relevance of methodological choices in the LCA of the New Zealand avocado sector

4.5.2.1 PCs as capital equipment

Previous packaging studies have demonstrated the environmental advantages of reusable crates (wooden and plastic) over single use cardboard boxes, as their multiple uses over an average lifetime of 20 years confer a relative environmental advantage compared with one-use packaging options (Abejón et al., 2020; Albrecht et al., 2013; Del Borghi et al., 2021; Silva & Molina-Besch, 2023; Tua et al., 2019). Moreover, for plastic crates the end-of-life recycling

results in secondary granulates which can be easily remanufactured into new crates (Albrecht et al., 2013). PCs were categorised as capital equipment in this study (assumed to be reused at least 50 times over their life cycle, based on industry opinion)³⁴, and therefore their life cycle-based impacts were excluded from the analysis (except for washing for reuse). If the PC manufacture and end-of-life stages are included and a 50-time reuse assumed, these life cycle stages contribute up to 0.4% of the total life cycle impacts of domestic transport using PCs, across impact categories. Therefore, this methodological assumption was appropriate for this study. However, in a single use scenario with no reuse, the impacts of these stages would account for 7-21% of the whole life cycle impacts for all the scenarios using PCs (Appendix D, Table D38).

Implication for VSS in New Zealand avocado sector

The PCs can be categorised as capital equipment and their life cycle-based environmental impacts excluded from the analysis provided they are reused at least 50 times over their life cycle. At this rate of reuse, the impacts are less than 1% of the total impact (including the orchard stage) for each impact category as required by EPD International (2019) (see Section 4.3.1). If the reuse frequency is lesser than 50, the manufacture and end-of-life stages should be included when developing indicators for a VSS.

4.5.2.2 National characterisation factor for water use

The AWARE method developed by Boulay et al. (2018) was used in this study to assess water use impacts. The method offers three types of characterisation factors depending on their level of disaggregation: national, sub-national, and watershed. Boulay & Lenoir (2020) recommend that whenever possible the more disaggregated characterisation factors (sub-national, and

³⁴ In their studies on packaging for food transport, Del Borghi et al. (2021) and Tua et al. (2019) assume a 50-time reuse scenario for plastic crates.

ideally watershed) be used for the analysis to reduce the uncertainty associated with watersheds that have variable rainfall and water scarcity levels.

In this study, the national level characterisation factors were used to model direct water use in the post-harvest stages of the supply chains. The results show that the impact of direct water use is very small compared with the indirect water use for cardboard manufacturing, and electricity used in the coolstore and packline; direct water use accounts for a maximum of 0.2% of the total packhouse water use impact result³⁵. Details about cardboard manufacturing were not available; also, it was not possible to disaggregate the indirect water use impacts as they were aggregated in the background processes in the modelling software. Thus, it was decided to model water use impacts using the national characterisation factor. However, if indirect water use sources can be determined, then use of the respective non-agricultural sub-national values could decrease the total packhouse water use impact – to varying degrees. For example, the national (unspecified) characterisation factor for New Zealand is 25, 10, and 6 times higher than the non-agricultural sub-national factors for the main regions where avocados are packed (Bay of Plenty, Northland, and Auckland respectively). If packaging is sourced from a more water-scarce region like Canterbury (the non-agricultural sub-national factor for Canterbury is only half that of the national factor), there would be a relatively smaller change (decrease) in impacts compared with the other regions.

Implication for VSS in New Zealand avocado sector

The post-harvest stages show the largest relative contribution to total impacts in the water use category compared with other impact categories (Figure 4.2). However, this reflects the fact that the national level CF was used to model these impacts whereas the lower, agricultural, sub-national factors were used at the orchard stage. The packhouse water use impacts could be

³⁵ Direct water use occurred in waterblasting the fruit, cleaning the packline and other miscellaneous packhouse activities.

considerably lower or higher than the orchard stage impacts if non-agricultural, sub-national figures were used for indirect water use instead. At the same time, it was determined that a majority of the post-harvest water use impacts are contributed by the packing stage, of which most impacts (>95%) are attributed to indirect water use, mainly for cardboard manufacturing, and electricity used in the coolstore and packline. Therefore, reduced direct volumetric water use at the packhouse does not have much potential to reduce water use impacts. Instead, a performance-based indicator to drive water use improvements should focus on cardboard manufacturing, and coolstore and packline electricity use.

4.5.3 Implications for use of LCA for post-harvest VSS indicators in other agri-food sectors

The avocado LCA study findings provided insights which can be applied to other agri-food sectors. One of the main insights is that the **post-harvest stages make an important contribution to the overall life cycle impacts** and this is supported by other literature on other product sectors as well, as shown in Section 4.5.1.1. However, the literature review (Section 4.2.4) showed that this is rarely considered in VSS criteria (only two wine VSS were identified that include post-harvest stages). Further, only one academic paper included the full life cycle for the experimental development of benchmarks for a VSS (Cossu et al., 2023). Therefore, post-harvest stages should be considered during VSS indicator development for other agri-food sectors as well.

Secondly, **other impact categories (apart from climate change) are relevant with respect to post-harvest impacts**. The literature review also showed that the VSS with LCA-based indicators mostly focus solely on climate change. However, as this avocado case study showed, including other impact categories can provide a more holistic view of impacts and avoid burden shifting. For example, while the average contribution of post-harvest stages to total life cycle impact was the highest for climate change (47%), other impact categories also showed notable impacts e.g. water use (41%) and terrestrial ecotoxicity (38%). Therefore, indicators for VSS in

other product sectors should be based on LCA studies which include an expanded range of impact categories rather than just climate change.

When developing sectoral VSS indicators, **individual LCA studies are important to identify the life cycle stage hotspots relevant to each sector.** As mentioned in Section 4.1, the biggest strength of an LCA as a decision-making tool is that it can help identify environmental hotspots (stages, impact categories, inputs, and activities), which can then be the focus for environmental performance improvement. While supply chains of different product sectors usually have the same basic framework (growing, packing, distributing, retail, consumption), different sectors can have very distinct supply chain dynamics, which can result in significant differences in the relative contribution of the stages to overall life cycle impact. For example, in the avocado case study, the orchard stage was the hotspot for most of the supply chain scenarios (except the airfreighting ones). This dynamic has been shown to be different for other sectors' supply chains, for example New Zealand apple and kiwifruit, where distribution is the hotspot, and wine, where glass bottle manufacturing for packaging is the hotspot (McLaren et al., 2021).

Another insight from the study is the desirability of developing **separate benchmarking indicators for domestic and international supply chains**, as they may require distinct inputs and activities. For example, in New Zealand domestic distribution of fruit uses PCs, plastic and wooden bins, and punnets; however, export packaging for fruit is always modular, e.g. SLTs with pocket packs for avocados (as shown in the study), and multilayer, cushioned/lined boxes for apples and kiwifruit (LEARNZ, 2025; Mithraratne et al., 2010; NZ Apples and Pears, 2024; Robertson et al., 2014). As shown in the avocado study, the export packaging impacts are higher than domestic packaging. Thus, two separate benchmarking indicators would be more appropriate for export and domestic supply chains.

The **sphere of stakeholder influence** should be a consideration when developing indicators for a VSS. As shown in the LCA study, the post-overseas port stages in the Australian supply chain had a notable contribution to life cycle impacts; however, it was suggested that these stages be

excluded from indicator development as they lie outside the sphere of stakeholder influence for a New Zealand-based VSS. The level of influence should be considered when developing VSS indicators for agri-food sectors in New Zealand as it is directly related to the ability of stakeholders to effect changes in their supply chains.

Lastly, **spatial considerations are important for some indicators where there is site-dependency in characterization of environmental impacts.** This was illustrated for water use in the avocado LCA study: the post-harvest water use impacts were calculated using national level characterisation factors, but the sub-national factors are quite variable. In such cases, sensitivity analyses should be undertaken to determine the likely influence of using sub-national factors. If this shows the post-harvest water use impacts are always inconsequential compared with orchard level impacts, then there would be no need to develop a water use indicator for the post-harvest stages. However, if the post-harvest results are significant when using one or more sub-national factors, then further efforts should be made to identify the location of the contributing processes, instead of using the aggregated national factor directly.

4.5.4 Limitations and future research

Other impact categories are relevant to post-harvest stages – such as acidification, marine ecotoxicity, primary and cumulative energy demand, ozone depletion, resource depletion, and photochemical ozone creation (Abejón et al., 2020; Albrecht et al., 2013; Frankowska et al., 2019; Tua et al., 2019). A future study should include them. Secondly, only 2 of 14 contacted packhouses provided data for this study, both located in the Bay of Plenty. A future study would benefit from a larger and more geographically diverse packhouse sample. Another limitation was the lack of detailed primary data on exact weight, dimension and composition (recycled vs. virgin material) of the various types of packaging used – especially cardboard packaging. A future study should include these considerations for better LCI representativeness. Lastly, while AVOCO data is largely representative of the avocado sector's export market, data from other domestic suppliers would provide a more holistic picture of the domestic supply chain and its

environmental impacts. In particular, it is often a challenge to obtain accurate data about a vehicle's actual load factors and backhaul percentages^{36,37} (Wakeland et al., 2012). The current study used ecoinvent transport datasets which considered utilisation rates based on average load factors (including empty return trips) for refrigerated transport in trucks (45%), trains and planes (50%), and container ships (70%). In reality, these percentages could be different. For example, McLaren et al. (2021) note that 68% of refrigerated containers containing fresh food for export markets return empty (i.e. 32% backhaul). Therefore, altering these utilisation rates could result in different results.

4.6 Conclusion

This study examined the role of LCA in developing performance-based indicators for VSS in agri-food systems, using the New Zealand avocado value chain as a case study. By mapping environmental impacts across orchard, post-harvest, and distribution stages, the research revealed that while production is often the recognised hotspot, post-harvest stages — particularly packing and distribution, can contribute a substantial share of life cycle impacts. In the case of avocados, post-harvest processes accounted for up to 41% of total impacts across impact categories, and distribution-related emissions sometimes rivalled or exceeded orchard-stage impacts for distant export markets. This suggests that excluding post-harvest stages from

³⁶ A vehicle's utilisation rate is based on its load factor (a measure of how much the vehicle is filled compared to its capacity) which considers whether a vehicle returns empty (deadhead) or with a full or partial load (backhaul). The lower the utilisation rate, the higher the distribution-related impacts (Wakeland et al., 2012). The importance of higher backhaul rates in particular on decreasing distribution impacts has been noted in literature (Iriarte et al., 2014; Payen et al., 2015; Svanes & Aronsson, 2013).

³⁷ Some agri-food supply chain studies assume 70-100% shipping backhaul (Accorsi et al., 2015; Barry, 2011; Boschiero et al., 2019; De Vlieghere et al., 2023) whereas others assume entirely empty return sea or road trips to allow for worst-case scenarios in the absence of relevant data (Brodt et al., 2013; Iriarte et al., 2014; Svanes & Aronsson, 2013; Svanes & Johnsen, 2019).

indicator design risks overlooking major opportunities for improvement. These findings therefore challenge the common tendency for VSS to focus predominantly on farm-level practices. Moreover, the study demonstrated the significance of including additional impact categories (other than climate change, which is generally the main focus of performance-based metrics in agri-food VSS).

In particular, the study informed the development of nuanced and supply chain-specific post-harvest indicators for the avocado sector in New Zealand. For example, separate benchmark indicators for export and domestic distribution, and impacts per unit of distance travelled rather than total distance covered by each supply chain. It also identified life cycle stages which need not be included in indicator development (like business transport at the packhouse), and those which have notable impacts but should be excluded on account of inadequate operational control (post-port stages). Methodological influences were also discussed, which can influence indicator development, like PC reuse and regional characterization factors for water use.

While applied here to avocados, this framework can be adapted for other export-oriented horticultural sectors, where distribution distances, storage requirements, and packaging choices strongly influence environmental profiles. Limitations of the research were noted and recommendations suggested for future research which can support both robust environmental accounting and feasible implementation within industry-led sustainability programmes like VSS.

References

- Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., & Fullana-i-Palmer, P. (2020). When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. *Resources, Conservation and Recycling*, 155, 104666. <https://doi.org/10.1016/j.resconrec.2019.104666>
- Accorsi, R., Versari, L., & Manzini, R. (2015). Glass vs. Plastic: Life Cycle Assessment of Extra-Virgin Olive Oil Bottles across Global Supply Chains. *Sustainability*, 7(3), Article 3. <https://doi.org/10.3390/su7032818>
- Agni Kalfagianni & Doris Fuchs. (2011). The Global GAP. In *Business Regulation and Non-State Actors*. Routledge.
- Akrong, R., Akorsu, A. D., Jha, P., & Agyenim, J. B. (2022). Assessing the trade and welfare effects of certification schemes: The case of GlobalGAP in Ghana's mango sector. *Scientific African*, 18, e01425. <https://doi.org/10.1016/j.sciaf.2022.e01425>
- Albrecht, S., Brandstetter, P., Beck, T., Fullana-i-Palmer, P., Grönman, K., Baitz, M., Deimling, S., Sandilands, J., & Fischer, M. (2013). An extended life cycle analysis of packaging systems for fruit and vegetable transport in Europe. *The International Journal of Life Cycle Assessment*, 18(8), 1549–1567. <https://doi.org/10.1007/s11367-013-0590-4>
- Amri, N. N., Anwar, S., Jupesta, J., & Sahari, B. (2023). Differences in greenhouse gas emission calculation guidelines for palm oil and its implication on mitigation planning. *IOP Conference Series: Earth and Environmental Science*, 1266(1), 012066. <https://doi.org/10.1088/1755-1315/1266/1/012066>
- ASC. (2025). *Accelerating Change in the Seafood Industry: ASC Launches Farm Standard*. <https://asc-aqua.org/news/accelerating-change-in-the-seafood-industry-asc-launches-farm-standard/> (Accessed 13 June 2025)
- Auld, G. (2010). Assessing Certification as Governance: Effects and Broader Consequences for Coffee. *The Journal of Environment & Development*, 19(2), 215–241. <https://doi.org/10.1177/1070496510368506>
- Baldo, G. L., Rollino, S., Stimmeder, G., & Fieschi, M. (2002). The use of LCA to develop eco-label criteria for hard floor coverings on behalf of the european flower. *The International Journal of Life Cycle Assessment*, 7(5), 269–275. <https://doi.org/10.1007/BF02978886>
- Barry, M. T. (2011). *Life Cycle Assessment and the New Zealand Wine Industry: A tool to support continuous environmental improvement* [Master's thesis, Massey University]. Massey

research online. <https://mro.massey.ac.nz/items/95e2dc84-1144-4e0b-9661-04c093141bf9>

- Barthel, M., Fava, J., James, K., Hardwick, A., & Khan, S. (2017). *Hotspots Analysis An overarching methodological framework and guidance for product and sector level application*. United Nations Environment Programme. Available for download at: <https://www.lifecycleinitiative.org/library/hotspots-analysis-an-overarching-methodological-framework-and-guidance-for-product-and-sector-level-application/>
- Basset-Mens, C., Edewa, A., & Gentil, C. (2019). An LCA of French beans from Kenya for decision-makers. *Indonesian Journal of Life Cycle Assessment and Sustainability*. <https://doi.org/10.52394/ijolcas.v3i1.45>
- Basset-Mens, C., Vannière, H., Grasselly, D., Heitz, H., Braun, A., Payen, S., Koch, P., & Biard, Y. (2016). Environmental impacts of imported and locally grown fruits for the French market: A cradle-to-farm-gate LCA study. *Fruits*, 71(2), 93–104. <https://doi.org/10.1051/fruits/2015050>
- Bellamy, A. S., Svensson, O., Van Den Brink, P. J., & Tedengren, M. (2016). What is in a label? Rainforest-Alliance certified banana production versus non-certified conventional banana production. *Global Ecology and Conservation*, 7, 39–48. <https://doi.org/10.1016/j.gecco.2016.05.002>
- Bessou, C. (2016). *PalmGHG, RSPO greenhouse gas calculator, scientific background* (22 pp.) [Conference presentation]. International Conference on Oil Palm and Environment (ICOPE 16-18 March 2016): Sustainable Palm Oil and Climate Change: The Way Forward through Mitigation and Adaptation. SMART Research Institute, CIRAD, WWF, Bali, Indonesia.
- Bessou, C., Basset-Mens, C., Latunussa, C., Vélú, A., Heitz, H., Vannière, H., & Caliman, J. P. (2016). Partial modelling of the perennial crop cycle misleads LCA results in two contrasted case studies. *The International Journal of Life Cycle Assessment*, 21(3), 297–310. <https://doi.org/10.1007/s11367-016-1030-z>
- Bessou, C., Basset-Mens, C., Tran, T., & Benoist, A. (2013). LCA applied to perennial cropping systems: A review focused on the farm stage. *The International Journal of Life Cycle Assessment*, 18(2), 340–361. <https://doi.org/10.1007/s11367-012-0502-z>
- Bessou, C., Chase, L. D. C., Henson, I. E., Abdul-Manan, A. F. N., Milà I Canals, L., Agus, F., Sharma, M., & Chin, M. (2014). Pilot application of PalmGHG, the Roundtable on Sustainable Palm Oil greenhouse gas calculator for oil palm products. *Journal of Cleaner Production*, 73, 136–145. <https://doi.org/10.1016/j.jclepro.2013.12.008>

- Bessou, C., Chase, L., Henson, I., & Abdul-Manan, A. F. N. (2012). PalmGHG, the RSPO greenhouse gas calculator for oil palm products. *8th International Conference on LCA in the Agri-Food Sector*, 1-4 October, 2012, Saint-Malo, France.
- Bianco, I., Thiébat, F., Carbonaro, C., Pagliolico, S., Blengini, G. A., & Comino, E. (2021). Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture. *Journal of Cleaner Production*, 324, 129249. <https://doi.org/10.1016/j.jclepro.2021.129249>
- Bonsucro. (2023). *Bonsucro production standard 2023*. Available for download at: <https://bonsucro.com/production-standard/>
- Boschiero, M., Zanutelli, D., Ciarapica, F. E., Fadanelli, L., & Tagliavini, M. (2019). Greenhouse gas emissions and energy consumption during the post-harvest life of apples as affected by storage type, packaging and transport. *Journal of Cleaner Production*, 220, 45–56. <https://doi.org/10.1016/j.jclepro.2019.01.300>
- Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: Assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, 23(2), 368–378. <https://doi.org/10.1007/s11367-017-1333-8>
- Boulay, A.M., & Lenoir, L. (2020). Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations. *Ecological Indicators*, 111, 106017. <https://doi.org/10.1016/j.ecolind.2019.106017>
- Brach, S., Walsh, G., & Shaw, D. (2018). Sustainable consumption and third-party certification labels: Consumers' perceptions and reactions. *European Management Journal*, 36(2), 254–265. <https://doi.org/10.1016/j.emj.2017.03.005>
- British Standards Institution (BSI). (2011). *2050 PAS 2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*. BSI.
- Brodts, S., Kramer, K. J., Kendall, A., & Feenstra, G. (2013). Comparing environmental impacts of regional and national-scale food supply chains: A case study of processed tomatoes. *Food Policy*, 42, 106–114. <https://doi.org/10.1016/j.foodpol.2013.07.004>
- Bush, S. R., Toonen, H., Oosterveer, P., & Mol, A. P. J. (2013). The 'devils triangle' of MSC certification: Balancing credibility, accessibility and continuous improvement. *Marine Policy*, 37, 288–293. <https://doi.org/10.1016/j.marpol.2012.05.011>

- Cambria, D., & Pierangeli, D. (2012). Application of a life cycle assessment to walnut tree (*Juglans regia* L.) high quality wood production: A case study in southern Italy. *Journal of Cleaner Production*, 23(1), 37–46. <https://doi.org/10.1016/j.jclepro.2011.10.031>
- Canwat, V. (2023). Value chains and sustainable development: A perspective of sustainable coffee value chains in East Africa. *Sustainable Development*, 31(2), 668–679. <https://doi.org/10.1002/sd.2444>
- Cashore, B., van Kooten, G. C., Vertinsky, I., Auld, G., & Affolderbach, J. (2005). Private or self-regulation? A comparative study of forest certification choices in Canada, the United States and Germany. *Forest Policy and Economics*, 7(1), 53–69. [https://doi.org/10.1016/S1389-9341\(03\)00011-X](https://doi.org/10.1016/S1389-9341(03)00011-X)
- Cashore, B. W., Auld, G., & Newsom, D. (2004). *Governing Through Markets: Forest Certification and the Emergence of Non-state Authority*. Yale University Press.
- Casolani, N., Chiodo, E., & Liberatore, L. (2023). Continuous Improvement of VIVA-Certified Wines: Analysis and Perspective of Greenhouse Gas Emissions. *Sustainability*, 15(3), Article 3. <https://doi.org/10.3390/su15032349>
- Casolani, N., & Liberatore, L. (2024). The Air Indicator of VIVA Certification for the Sustainability of Italian Wine: Analysis and Perspectives. In G. Lagioia, A. Paiano, V. Amicarelli, T. Gallucci, & C. Ingrao (Eds.), *Innovation, Quality and Sustainability for a Resilient Circular Economy* (pp. 161–167). Springer International Publishing. https://doi.org/10.1007/978-3-031-28292-8_21
- Castellani, V., Sala, S., & Benini, L. (2017). Hotspots analysis and critical interpretation of food life cycle assessment studies for selecting eco-innovation options and for policy support. *Journal of Cleaner Production*, 140, 556–568. <https://doi.org/10.1016/j.jclepro.2016.05.078>
- Cerutti, A. K., Beccaro, G. L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., & Bounous, G. (2014). Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. *Journal of Cleaner Production*, 73, 125–135. <https://doi.org/10.1016/j.jclepro.2013.09.017>
- Clift, R. (1993). Life cycle assessment and ecolabelling. *Journal of Cleaner Production*, 1(3–4), 155–159. [https://doi.org/10.1016/0959-6526\(93\)90006-W](https://doi.org/10.1016/0959-6526(93)90006-W)
- Cornago, S., Tan, Y. S., Ramakrishna, S., & Choong Low, J. S. (2022). Temporal Hotspot Identification using Dynamic Life Cycle Inventory: Which are the Critical Time-spans within

- the Product Life Cycle? *Procedia CIRP*, 105, 249–254.
<https://doi.org/10.1016/j.procir.2022.02.041>
- Cossu, D., Zanchi, L., Maranghi, S., Zamagni, A., Gaias, G., Duce, P., & Vagnoni, E. (2023). Ecolabelling for improving sustainability of agri-food supply chain: An experimental implementation of the made green in Italy scheme on the hard sheep milk cheese. *Cleaner Environmental Systems*, 100153. <https://doi.org/10.1016/j.cesys.2023.100153>
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), Article 3. <https://doi.org/10.1038/s43016-021-00225-9>
- D’Ammaro, D., Capri, E., Valentino, F., Grillo, S., Fiorini, E., & Lamastra, L. (2021). Benchmarking of carbon footprint data from the Italian wine sector: A comprehensive and extended analysis. *Science of The Total Environment*, 779, 146416.
<https://doi.org/10.1016/j.scitotenv.2021.146416>
- Darnall, N., Ji, H., & Vázquez-Brust, D. A. (2018). Third-Party Certification, Sponsorship, and Consumers’ Ecolabel Use. *Journal of Business Ethics*, 150(4), 953–969.
<https://doi.org/10.1007/s10551-016-3138-2>
- De Vlieghere, A., van Veghel, A. S., & Geeraerd, A. (2023). Life cycle assessment of importing canned tuna into Aruba through different supply chains, in varying can sizes and in oils, brine or tomato sauce. *The International Journal of Life Cycle Assessment*.
<https://doi.org/10.1007/s11367-023-02207-4>
- Del Borghi, A., Parodi, S., Moreschi, L., & Gallo, M. (2021). Sustainable packaging: An evaluation of crates for food through a life cycle approach. *The International Journal of Life Cycle Assessment*, 26(4), 753–766. <https://doi.org/10.1007/s11367-020-01813-w>
- Dias, G. M., Ayer, N. W., Khosla, S., Van Acker, R., Young, S. B., Whitney, S., & Hendricks, P. (2017). Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. *Journal of Cleaner Production*, 140, 831–839. <https://doi.org/10.1016/j.jclepro.2016.06.039>
- Dietz, T., & Grabs, J. (2022). Additionality and Implementation Gaps in Voluntary Sustainability Standards. *New Political Economy*, 27(2), 203–224.
<https://doi.org/10.1080/13563467.2021.1881473>

- Dietz, T., Grabs, J., & Chong, A. E. (2021). Mainstreamed voluntary sustainability standards and their effectiveness: Evidence from the Honduran coffee sector. *Regulation & Governance*, 15(2), 333–355. <https://doi.org/10.1111/rego.12239>
- Dijkman, T. J., Basset-Mens, C., Antón, A., & Núñez, M. (2018). LCA of Food and Agriculture. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 723–754). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_29
- EPD International. (2019). *PCR Fruits and nuts. Product Category Classification UN CPC 013. 2019-01, Version 1.01. Valid until 21/01/2023*. (Version 1.01) [UN CPC 013]. Available for download at: <https://api.environdec.com/api/v1/EPDLibrary/Files/40cecf40-cb08-4a86-174e-08dc25c78130/Data>
- European Commission, Umweltbundesamt, Pré., 2.0 LCA., RISE., & Heid und Partner Rechtsanwälte GmbH. (2021). *Study on the implementation of life cycle assessment and environmental footprint methods in the context of public procurement: Final report*. Publications Office. Available for download at: <https://data.europa.eu/doi/10.2779/74025>
- FAO. (2014). *SAFA guidelines: Sustainability assessment of food and agriculture systems* (Version 3.0). Food and Agriculture Organization of the United Nations. Available for download at: <https://openknowledge.fao.org/items/84c84661-7172-415c-b66e-7c1eee5db675>
- FAO. (2019). *The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction*. Food and Agriculture Organization of the United Nations. Available for download at: <https://www.un-ilibrary.org/content/books/9789210046268>
- Ferrara, C., & De Feo, G. (2018). Life Cycle Assessment Application to the Wine Sector: A Critical Review. *Sustainability*, 10(2), Article 2. <https://doi.org/10.3390/su10020395>
- Figueiredo, F., Castanheira, É. G., Feliciano, M., Rodrigues, M. Â., Peres, A., Maia, F., Ramos, A., Carneiro, J., Coroama, V. C., & Freire, F. (2013). *Carbon footprint of apple and pear: Orchards, storage and distribution*. Energy for Sustainability 2013 Sustainable Cities: Designing for People and the Planet Coimbra, 8 to 10 September 2013, Coimbra.
- Frankowska, A., Jeswani, H. K., & Azapagic, A. (2019). Life cycle environmental impacts of fruits consumption in the UK. *Journal of Environmental Management*, 248, 109111. <https://doi.org/10.1016/j.jenvman.2019.06.012>
- Freidberg, S. (2017). Big Food and Little Data: The Slow Harvest of Corporate Food Supply Chain Sustainability Initiatives. *Annals of the American Association of Geographers*, 107(6), 1389–1406. <https://doi.org/10.1080/24694452.2017.1309967>

- Galindro, B. M., Zanghelini, G. M., & Soares, S. R. (2019). Use of benchmarking techniques to improve communication in life cycle assessment: A general review. *Journal of Cleaner Production*, 213, 143–157. <https://doi.org/10.1016/j.jclepro.2018.12.147>
- Galletto, L., & Barisan, L. (2019). Carbon Footprint as a Lever for Sustained Competitive Strategy in Developing a Smart Oenology: Evidence from an Exploratory Study in Italy. *Sustainability*, 11(5), Article 5. <https://doi.org/10.3390/su11051483>
- Gasso, V., Barber, A., Moller, H., Bayonne, E., Oudshoorn, F. W., & Sørensen, C. G. (2025). Benchmarking for locally tuned sustainability: The case of energy and water use in New Zealand vineyards. *Environmental and Sustainability Indicators*, 25, 100536. <https://doi.org/10.1016/j.indic.2024.100536>
- Gather, J., & Wollni, M. (2022). Setting the standard: Does Rainforest Alliance Certification increase environmental and socio-economic outcomes for small-scale coffee producers in Rwanda? *Applied Economic Perspectives and Policy*, 44(4), 1807–1825. <https://doi.org/10.1002/aepp.13307>
- Ghadimi, P., Wang, C., Azadnia, A. H., Lim, M. K., & Sutherland, J. W. (2019). Life cycle-based environmental performance indicator for the coal-to-energy supply chain: A Chinese case application. *Resources, Conservation and Recycling*, 147, 28–38. <https://doi.org/10.1016/j.resconrec.2019.04.021>
- Goossens, Y., Annaert, B., De Tavernier, J., Mathijs, E., Keulemans, W., & Geeraerd, A. (2017). Life cycle assessment (LCA) for apple orchard production systems including low and high productive years in conventional, integrated and organic farms. *Agricultural Systems*, 153, 81–93. <https://doi.org/10.1016/j.agsy.2017.01.007>
- Gowans, G. (2023). *Dutch supermarket adjusts supply chain and logistics to cut out air freight*. <https://trans.info/en/dutch-supermarket-cuts-out-air-freight-327318> (Accessed 15 May 2024)
- Hatanaka, M., Bain, C., & Busch, L. (2005). Third-party certification in the global agrifood system. *Food Policy*, 30(3), 354–369. <https://doi.org/10.1016/j.foodpol.2005.05.006>
- Hatanaka, M., Konefal, J., Strube, J., Glenna, L., & Conner, D. (2022). Data-Driven Sustainability: Metrics, Digital Technologies, and Governance in Food and Agriculture*. *Rural Sociology*, 87(1), 206–230. <https://doi.org/10.1111/ruso.12415>

- Hélias, A., & Servien, R. (2021). Normalization in LCA: How to ensure consistency? *The International Journal of Life Cycle Assessment*, 26(6), 1117–1122.
<https://doi.org/10.1007/s11367-021-01897-y>
- Hélias, A., van der Werf, H. M. G., Soler, L.-G., Aggeri, F., Dourmad, J.-Y., Julia, C., Nabec, L., Pellerin, S., Ruffieux, B., & Trystram, G. (2022). Implementing environmental labelling of food products in France. *The International Journal of Life Cycle Assessment*, 27(7), 926–931.
<https://doi.org/10.1007/s11367-022-02071-8>
- Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual*. Routledge. <https://doi.org/10.4324/9781849775526>
- Indian Ministry of Agriculture. (2011). *Technical standards and protocol for fruit ripening chambers in India*. Available for download at: <https://nhb.gov.in/guidelines/cold-storage-guidelines.html>
- Ingwersen, W. W. (2012). Life cycle assessment of fresh pineapple from Costa Rica. *Journal of Cleaner Production*, 35, 152–163. <https://doi.org/10.1016/j.jclepro.2012.05.035>
- Iriarte, A., Almeida, M. G., & Villalobos, P. (2014). Carbon footprint of premium quality export bananas: Case study in Ecuador, the world's largest exporter. *Science of The Total Environment*, 472, 1082–1088. <https://doi.org/10.1016/j.scitotenv.2013.11.072>
- ISEAL Alliance. (2020). *Sustainability Benchmarking Good Practice Guide*. Available for download at: <https://isealalliance.org/get-involved/resources/sustainability-benchmarking-good-practice-guide-v11>
- ISO (2006). *Environmental management — Life cycle assessment — Principles and framework (ISO 14040:2006)*. International Organization for Standardization, Geneva, Switzerland.
- ITC. (2023). *StandardsMap—The world's largest database for sustainability standards*. <https://www.standardsmap.org/en/home> (Accessed 8 August 2024)
- Kamalakkannan, S., Wasala, W. M. C. B., Kulatunga, A. K., Gunawardena, C. R., Bandara, D. M. S. P., Jayawardana, J., Rathnayake, R. M. R. N. K., Wijewardana, R. M. N. A., Weerakkody, W. A. P., Ferguson, I., & Chandrakumar, C. (2022). Life Cycle Assessment of Food Loss Impacts: Case of Banana Postharvest Losses in Sri Lanka. *Procedia CIRP*, 105, 859–864.
<https://doi.org/10.1016/j.procir.2022.02.142>
- Kanafani, K., Kjær Zimmermann, R., Nygaard Rasmussen, F., & Birgisdóttir, H. (2021). Learnings from Developing a Context-Specific LCA Tool for Buildings—The Case of LCAByg 4. *Sustainability*, 13(3), Article 3. <https://doi.org/10.3390/su13031508>

- Kemper, L., Sampson, G., Bermúdez, S., Schlatter, B., Luna, E., Dang, T.D., and Willer, H. (2024). *The state of sustainable markets 2024: Statistics and emerging trends*. International Trade Centre, Geneva. Available for download at:
<https://www.intracen.org/resources/publications/state-of-sustainable-markets-2024>
- Keyes, S. (2013). *Evaluating the environmental impacts of conventional and organic production in Nova Scotia, Canada, through Life Cycle Assessment* [Master's thesis, Dalhousie University, Canada]. Online thesis collection, <https://dalspace.library.dal.ca/items/639c8ad2-cb8d-40ae-a136-ffe8d65754cd>
- Konefal, J., Hatanaka, M., Strube, J., Glenna, L., & Conner, D. (2022). Sustainability assemblages: From metrics development to metrics implementation in United States agriculture. *Journal of Rural Studies*, 92, 502–509. <https://doi.org/10.1016/j.jrurstud.2019.10.023>
- Kühne, S. J., Reijnen, E., Laasner Vogt, L., & Baumgartner, M. (2023). Can carbon labels encourage green food choices? *Frontiers in Psychology*, 13.
<https://www.frontiersin.org/articles/10.3389/fpsyg.2022.902869>
- Lavers Westin, A., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., & Rydberg, T. (2019). Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. *Journal of Cleaner Production*, 226, 526–539.
<https://doi.org/10.1016/j.jclepro.2019.04.036>
- Lazzerini, G., Lucchetti, S., & Nicese, F. P. (2014). Analysis of greenhouse gas emissions from ornamental plant production: A nursery level approach. *Urban Forestry & Urban Greening*, 13(3), 517–525. <https://doi.org/10.1016/j.ufug.2014.02.004>
- LEARNZ. (2025). *Storing and Exporting Apples* | LEARNZ.
<https://www.learnz.org.nz/primaryindustries192/bg-easy-f/storing-and-exporting-apples>
(Accessed 5 June 2025)
- Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., & Raubenheimer, D. (2022). Global food-miles account for nearly 20% of total food-systems emissions. *Nature Food*, 3(6), Article 6.
<https://doi.org/10.1038/s43016-022-00531-w>
- Lo-Iacono-Ferreira, V. G., Viñoles-Cebolla, R., Bastante-Ceca, M. J., & Capuz-Rizo, S. F. (2020). Transport of Spanish fruit and vegetables in cardboard boxes: A carbon footprint analysis. *Journal of Cleaner Production*, 244, 118784. <https://doi.org/10.1016/j.jclepro.2019.118784>
- Majumdar, S., & McLaren, S. J. (2023). Towards use of life cycle-based indicators to support continuous improvement in the environmental performance of avocado orchards in New

- Zealand. *The International Journal of Life Cycle Assessment*, 29, 192–217.
<https://doi.org/10.1007/s11367-023-02238-x>
- Marx, A., Depoorter, C., & Vanhaecht, R. (2022). Voluntary Sustainability Standards: State of the Art and Future Research. *Standards*, 2(1), Article 1.
<https://doi.org/10.3390/standards2010002>
- Match, B. (2020). *The time is ripe, Coles' \$43 million ripening facility reaps solar harvest*. Pv Magazine Australia. <https://www.pv-magazine-australia.com/2020/08/18/the-time-is-ripe-coles-43-million-ripening-facility-reaps-solar-harvest/> (Accessed 18 August 2024)
- McAloone, T. C., & Pigosso, D. C. A. (2018). Ecodesign Implementation and LCA. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 545–576). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_23
- McGarr-O'Brien, K., Herron, J., Shalloo, L., De Boer, I. J. M., & De Olde, E. M. (2023). Characterising sustainability certification standards in dairy production. *Animal*, 17(7), 100863.
<https://doi.org/10.1016/j.animal.2023.100863>
- McLaren, S. J. (2009). Food miles: fact or fiction? in B. Frame, R. Gordon, & C. Mortimer (Eds.), *Hatched. The Capacity for Sustainable Development*, Landcare Research, Lincoln. Available for download at:
<https://cdm20022.contentdm.oclc.org/digital/collection/p20022coll14/id/58>
- McLaren, S., Clothier, B., Barber, A., McNally, S., Bullen, L., Mazzetto, A., & Ledgard, S. (2021). *Updating the carbon footprints for selected New Zealand agricultural products*. Available for download at: <https://www.mpi.govt.nz/dmsdocument/51079-Updating-the-carbon-footprint-for-selected-New-Zealand-agricultural-products-an-update-for-apples-kiwifruit-and-wine/>
- Meemken, E. M. (2020). Do smallholder farmers benefit from sustainability standards? A systematic review and meta-analysis. *Global Food Security*, 26, 100373.
<https://doi.org/10.1016/j.gfs.2020.100373>
- Merli, R., Preziosi, M., & Acampora, A. (2018). Sustainability experiences in the wine sector: Toward the development of an international indicators system. *Journal of Cleaner Production*, 172, 3791–3805. <https://doi.org/10.1016/j.jclepro.2017.06.129>

- Michalský, M., & Hooda, P. S. (2015). Greenhouse gas emissions of imported and locally produced fruit and vegetable commodities: A quantitative assessment. *Environmental Science & Policy*, 48, 32–43. <https://doi.org/10.1016/j.envsci.2014.12.018>
- Milà i Canals, L., Domènèch, X., Rieradevall, J., Puig, R., & Fullana, P. (2002). Use of Life Cycle assessment in the procedure for the establishment of environmental criteria in the catalan ECO-label of leather. *The International Journal of Life Cycle Assessment*, 7(1), 39–46. <https://doi.org/10.1007/BF02978908>
- Milà I Canals, L., Muñoz, I., Hospido, A., Plassman, K., & McLaren, S. (2008). *Life Cycle Assessment (LCA) of domestic vs. Imported vegetables. Case studies on broccoli, salad crops and green beans*. <https://www.surrey.ac.uk/sites/default/files/2021-06/life-cycle-assessment-domestic-vs-imported-vegetables.pdf>
- Mithraratne, N., Barber, A., & McLaren, S. J. (2010). *Carbon footprinting of the kiwifruit supply chain—Report on methodology and scoping study*. https://www.landcareresearch.co.nz/assets/researchpubs/Kiwifruit_Methodology_Report_2010.pdf
- Mohan, R. (2018). *Use of life cycle assessment (LCA) to facilitate continuous improvement of on-farm environmental performance: A sheep dairy case study* [Master's thesis, Massey University]. Massey research online. <https://mro.massey.ac.nz/handle/10179/14849>
- Mungkung, R., Udo De Haes, H., & Clift, R. (2006). Potentials and Limitations of Life Cycle Assessment in Setting Ecolabelling Criteria: A Case Study of Thai Shrimp Aquaculture Product (5 pp). *The International Journal of Life Cycle Assessment*, 11(1), 55–59. <https://doi.org/10.1065/lca2006.01.238>
- Nahlik, M. J., Kaehr, A. T., Chester, M. V., Horvath, A., & Taptich, M. N. (2016). Goods Movement Life Cycle Assessment for Greenhouse Gas Reduction Goals: Goods Movement LCA for GHG Reduction Goals. *Journal of Industrial Ecology*, 20(2), 317–328. <https://doi.org/10.1111/jiec.12277>
- Neitzel, H. (1997). Application of life cycle assessment in environmental labelling. *The International Journal of Life Cycle Assessment*, 2(4), 241–249. <https://doi.org/10.1007/BF02978422>
- Nicese, F.P. and Lazzarini, G. (2013). CO₂ sources and sink in ornamental plant nurseries. *Acta Horticulturae*, 990, 91-98. <https://doi-org.ezproxy.massey.ac.nz/10.17660/ActaHortic.2013.990.8>

- NZ Apples and Pears. (2024). *Journey Through a Season—Packed Fruit*.
<https://www.applesandpears.nz/our-apples-pears/journey-through-a-season/> (Accessed 10 August 2025)
- Oosterveer, S. B., Peter. (2019). *Governing Sustainable Seafood*. Routledge.
<https://doi.org/10.4324/9781315780429>
- Osmundsen, T. C., Amundsen, V. S., Alexander, K. A., Asche, F., Bailey, J., Finstad, B., Olsen, M. S., Hernández, K., & Salgado, H. (2020). The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Global Environmental Change*, 60, 102025. <https://doi.org/10.1016/j.gloenvcha.2019.102025>
- Paratscha, R., Von Der Thannen, M., Smutny, R., Lampalzer, T., Strauss, A., & Rauch, H. P. (2019). Development of LCA benchmarks for Austrian torrent control structures. *The International Journal of Life Cycle Assessment*, 24(11), 2035–2053. <https://doi.org/10.1007/s11367-019-01618-6>
- Parra-Paitan, C., Zu Ermgassen, E. K. H. J., Meyfroidt, P., & Verburg, P. H. (2023). Large gaps in voluntary sustainability commitments covering the global cocoa trade. *Global Environmental Change*, 81, 102696. <https://doi.org/10.1016/j.gloenvcha.2023.102696>
- Payen, S., Basset-Mens, C., & Perret, S. (2015). LCA of local and imported tomato: An energy and water trade-off. *Journal of Cleaner Production*, 87, 139–148.
<https://doi.org/10.1016/j.jclepro.2014.10.007>
- Pedreschi, R., Ponce, E., Hernández, I., Fuentealba, C., Urbina, A., González-Fernández, J. J., Hormaza, J. I., Campos, D., Chirinos, R., & Aguayo, E. (2022). Short vs. Long-Distance Avocado Supply Chains: Life Cycle Assessment Impact Associated to Transport and Effect of Fruit Origin and Supply Conditions Chain on Primary and Secondary Metabolites. *Foods (Basel, Switzerland)*, 11(12), 1807. <https://doi.org/10.3390/foods11121807>
- Petruzzelli, M., Ihle, R., Colitti, S., & Vittuari, M. (2023). The role of short food supply chains in advancing the global agenda for sustainable food systems transitions. *Cities*, 141, 104496. <https://doi.org/10.1016/j.cities.2023.104496>
- Pizzol, M., Laurent, A., Sala, S., Weidema, B., Verones, F., & Koffler, C. (2017). Normalisation and weighting in life cycle assessment: Quo vadis? *The International Journal of Life Cycle Assessment*, 22(6), 853–866. <https://doi.org/10.1007/s11367-016-1199-1>
- Potter, C., Bastounis, A., Hartmann-Boyce, J., Stewart, C., Frie, K., Tudor, K., Bianchi, F., Cartwright, E., Cook, B., Rayner, M., & Jebb, S. A. (2021). The Effects of Environmental

- Sustainability Labels on Selection, Purchase, and Consumption of Food and Drink Products: A Systematic Review. *Environment and Behavior*, 53(8), 891–925.
<https://doi.org/10.1177/0013916521995473>
- Pryshlakivsky, J., & Searcy, C. (2021). Life Cycle Assessment as a decision-making tool: Practitioner and managerial considerations. *Journal of Cleaner Production*, 309, 127344.
<https://doi.org/10.1016/j.jclepro.2021.127344>
- Repar, N., Jan, P., Dux, D., Nemecek, T., & Doluschitz, R. (2017). Implementing farm-level environmental sustainability in environmental performance indicators: A combined global-local approach. *Journal of Cleaner Production*, 140, 692–704.
<https://doi.org/10.1016/j.jclepro.2016.07.022>
- Ridoutt, B., Sanguansri, P., Bonney, L., Crimp, S., Lewis, G., & Lim-Camacho, L. (2016). Climate Change Adaptation Strategy in the Food Industry—Insights from Product Carbon and Water Footprints. *Climate*, 4(2), Article 2. <https://doi.org/10.3390/cli4020026>
- Ritchie, H., & Roser, M. (2024). Very little of global food is transported by air; this greatly reduces the climate benefits of eating local. *Our World in Data*.
<https://ourworldindata.org/food-transport-by-mode> (Accessed 27 August 2024)
- Robertson, K., Garnham, M., & Symes, W. (2014). Life cycle carbon footprint of the packaging and transport of New Zealand kiwifruit. *The International Journal of Life Cycle Assessment*, 19(10), 1693–1704. <https://doi.org/10.1007/s11367-014-0775-5>
- Schwarz, J., Schuster, M., Annaert, B., Maertens, M., & Mathijs, E. (2016). Sustainability of Global and Local Food Value Chains: An Empirical Comparison of Peruvian and Belgian Asparagus. *Sustainability*, 8(4), 344. <https://doi.org/10.3390/su8040344>
- Scrimgeour, F., & Locke, S. (2015). *Review of Kiwifruit New Zealand* (SSRN Scholarly Paper 3286701). Social Science Research Network. <https://doi.org/10.2139/ssrn.3286701>
- Silva, N., & Molina-Besch, K. (2023). Replacing plastic with corrugated cardboard: A carbon footprint analysis of disposable packaging in a B2B global supply chain—A case study. *Resources, Conservation and Recycling*, 191, 106871.
<https://doi.org/10.1016/j.resconrec.2023.106871>
- Sim, S., Barry, M., Clift, R., & Cowell, S. J. (2007). The relative importance of transport in determining an appropriate sustainability strategy for food sourcing: A case study of fresh produce supply chains. *The International Journal of Life Cycle Assessment*, 12(6), 422–431.
<https://doi.org/10.1065/lca2006.07.259>

- Solarz, K., Raftowicz, M., Kachniarz, M., & Dradrach, A. (2023). Back to Locality? Demand Potential Analysis for Short Food Supply Chains. *International Journal of Environmental Research and Public Health*, 20(4), 3641. <https://doi.org/10.3390/ijerph20043641>
- Sonnemann, G., & Margni, M. (Eds.). (2015). *Life Cycle Management*. Springer Netherlands. <https://doi.org/10.1007/978-94-017-7221-1>
- South Pole. (2020). *Review of Bonsucro Production Standard GHG Emission Indicators. Final Review Report*. https://bonsucro.com/wp-content/uploads/2020/12/QC-EHU-Bonsucro-Production-standard-review_working-session_ppt-NT-com....pdf
- Stoessel, F., Juraske, R., Pfister, S., & Hellweg, S. (2012). Life Cycle Inventory and Carbon and Water FoodPrint of Fruits and Vegetables: Application to a Swiss Retailer. *Environmental Science & Technology*, 46(6), 3253–3262. <https://doi.org/10.1021/es2030577>
- Svanes, E., & Aronsson, A. K. S. (2013). Carbon footprint of a Cavendish banana supply chain. *The International Journal of Life Cycle Assessment*, 18(8), 1450–1464. <https://doi.org/10.1007/s11367-013-0602-4>
- Svanes, E., & Johnsen, F. M. (2019). Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. *Journal of Cleaner Production*, 238, 117773. <https://doi.org/10.1016/j.jclepro.2019.117773>
- Tallontire, A., Nelson, V., Dixon, J., & Benton, T. G. (2012). *A review of the literature and knowledge of standards and certification systems in agricultural production and farming systems (NRI working paper series on sustainability standards No. 2)*. Natural Resources Institute, Chatham, U.K.
- Tao, J., Li, L., & Yu, S. (2018). An innovative eco-design approach based on integration of LCA, CAD\CAE and optimization tools, and its implementation perspectives. *Journal of Cleaner Production*, 187, 839–851. <https://doi.org/10.1016/j.jclepro.2018.03.213>
- Tayleur, C., Balmford, A., Buchanan, G. M., Butchart, S. H. M., Corlet Walker, C., Ducharme, H., Green, R. E., Milder, J. C., Sanderson, F. J., Thomas, D. H. L., Tracewski, L., Vickery, J., & Phalan, B. (2018). Where are commodity crops certified, and what does it mean for conservation and poverty alleviation? *Biological Conservation*, 217, 36–46. <https://doi.org/10.1016/j.biocon.2017.09.024>
- Tayleur, C., Balmford, A., Buchanan, G. M., Butchart, S. H. M., Ducharme, H., Green, R. E., Milder, J. C., Sanderson, F. J., Thomas, D. H. L., Vickery, J., & Phalan, B. (2017). Global Coverage of

- Agricultural Sustainability Standards, and Their Role in Conserving Biodiversity. *Conservation Letters*, 10(5), 610–618. <https://doi.org/10.1111/conl.12314>
- thinkstep ANZ. (2023). *LCA of assessment of New Zealand-farmed King salmon*. Available for download at: <https://www.thinkstep-anz.com/resrc/case-studies/lca-nz-farmed-king-salmon/>
- Traldi, R. (2021). Progress and pitfalls: A systematic review of the evidence for agricultural sustainability standards. *Ecological Indicators*, 125, 107490. <https://doi.org/10.1016/j.ecolind.2021.107490>
- Tua, C., Biganzoli, L., Grosso, M., & Rigamonti, L. (2019). Life Cycle Assessment of Reusable Plastic Crates (RPCs). *Resources*, 8(2), 110. <https://doi.org/10.3390/resources8020110>
- Tubiello, F. N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S. Y., Halldórudóttir Heiðarsdóttir, H., Wanner, N., Quadrelli, R., Rocha Souza, L., Benoit, P., Hayek, M., Sandalow, D., Mencos Contreras, E., Rosenzweig, C., Rosero Moncayo, J., Conforti, P., & Torero, M. (2022). Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth System Science Data*, 14(4), 1795–1809. <https://doi.org/10.5194/essd-14-1795-2022>
- UNCTAD. (2021). *Better Trade for Sustainable Development: The Role of Voluntary Sustainability Standards*. United Nations. <https://doi.org/10.18356/9789210058865>
- UNFSS. (2012). *Voluntary Sustainability Standards: Today's landscape of issues & initiatives to achieve public policy objectives. Part 2*. https://unfss.org/wp-content/uploads/2012/05/unfss-report-initiatives-2_draft_lores.pdf
- UNFSS, FAO, ITC, UNCTAD, UNEP, & UNDO. (2020). *Scaling up Voluntary Sustainability Standards through Sustainability Public Procurement and Trade Policy*. https://unctad.org/system/files/official-document/unfss_4th_2020_en.pdf
- United Nations. (2023). *The Sustainable Development Goals Report. Special edition. Towards a Rescue Plan for People and Planet*. <https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf>
- van der Ven, H., & Barmes, D. (2023). The uneasy marriage of private standards and public policies for sustainable commodity governance. *Business Strategy and the Environment*, n/a(n/a). <https://doi.org/10.1002/bse.3424>
- Vanderhaegen, K., Akoyi, K. T., Dekoninck, W., Jocqué, R., Muys, B., Verbist, B., & Maertens, M. (2018). Do private coffee standards ‘walk the talk’ in improving socio-economic and

- environmental sustainability? *Global Environmental Change*, 51, 1–9.
<https://doi.org/10.1016/j.gloenvcha.2018.04.014>
- Veale, M., Renard, N., & Seixas, R. (2015). *Moving to metrics: Opportunities and challenges of performance-based sustainability standards*. In N. Renard (Ed.), *S.A.P.I.E.N.S. Perspectives integrating environment & society*, 8(1). <https://doi.org/10.4000/sapiens.1713>
- Viart, N., & Rein, P. W. (2013). The development and implementation of the Bonsucro standards for promoting the sustainability of sugarcane products. *Sugar Industry*, 707–712.
<https://doi.org/10.36961/si15048>
- Viart, N., Seixas, R., & Slavinski, S. (2016). Evaluation of the Bonsucro calculator as a sustainability performance benchmarking tool in the sugarcane sector. *Proceedings of the International Society of Sugar Cane Technologists*, 5-8 December 2016 (vol. 29, pp. 371-378), International Society of Sugar Cane Technologists. Chiang Mai, Thailand.
- Villacis, A., Alwang, J., & Barrera, V. (2022). Cacao value chains and credence attributes: Lessons from Ecuador. *Journal of Agribusiness in Developing and Emerging Economies*, 12(4), 549–566. <https://doi.org/10.1108/JADEE-10-2021-0267>
- Vince, J., & Haward, M. (2019). Hybrid governance in aquaculture: Certification schemes and third party accreditation. *Aquaculture*, 507, 322–328.
<https://doi.org/10.1016/j.aquaculture.2019.04.041>
- Vinyes, E., Asin, L., Alegre, S., Muñoz, P., Boschmonart, J., & Gasol, C. M. (2017). Life Cycle Assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. *Journal of Cleaner Production*, 149, 313–320.
<https://doi.org/10.1016/j.jclepro.2017.02.102>
- Wagenvoort, H. (2022). Lidl phases out air freight for fresh produce. *Supply Chain Movement*.
<https://www.supplychainmovement.com/lidl-phases-out-air-freight-for-fresh-produce/>
 (Accessed 17 January 2024)
- Wakeland, W., Cholette, S., & Venkat, K. (2012). Food transportation issues and reducing carbon footprint. In J. I. Boye & Y. Arcand (Eds.), *Green Technologies in Food Production and Processing* (pp. 211–236). Springer US. https://doi.org/10.1007/978-1-4614-1587-9_9
- Wenzel, H. (1998). Application dependency of LCA methodology: Key variables and their mode of influencing the method. *The International Journal of Life Cycle Assessment*, 3(5), 281–288.
<https://doi.org/10.1007/BF02979837>

- Williams, V., Flannery, O., & Patel, A. (2023). Eco-score labels on meat products: Consumer perceptions and attitudes towards sustainable choices. *Food Quality and Preference*, 111, 104973. <https://doi.org/10.1016/j.foodqual.2023.104973>
- Winther, U., Hognes, E. S., Jafarzadeh, S., & Ziegler, F. (2020). *Greenhouse gas emissions of Norwegian seafood products in 2017*.
https://www.sintef.no/contentassets/25338e561f1a4270a59ce25bcbc926a2/report-carbon-footprint-norwegian-seafood-products-2017_final_040620.pdf/
- WRI, & WBCSD. (2011). *GHG Protocol Standard—Product Life Cycle Accounting and Reporting*. Available for download at: <https://ghgprotocol.org/product-standard>
- Zanchini, R., Blanc, S., Pippinato, L., Poratelli, F., Bruzzese, S., & Brun, F. (2022). Enhancing wood products through ENplus, FSC and PEFC certifications: Which attributes do consumers value the most? *Forest Policy and Economics*, 142, 102782.
<https://doi.org/10.1016/j.forpol.2022.102782>
- Ziegler, F., & Hilborn, R. (2023). Fished or farmed: Life cycle impacts of salmon consumer decisions and opportunities for reducing impacts. *Science of The Total Environment*, 854, 158591. <https://doi.org/10.1016/j.scitotenv.2022.158591>
- Ziegler, F., Jafarzadeh, S., Skontorp Hognes, E., & Winther, U. (2022). Greenhouse gas emissions of Norwegian seafoods: From comprehensive to simplified assessment. *Journal of Industrial Ecology*, 26(6), 1908–1919. <https://doi.org/10.1111/jiec.13150>

Chapter 5 An nLCA approach to support consumer meal decisions: a New Zealand case study of toppings on toast

This chapter addresses the consumption aspect of SCP for SFS by developing a nutritional LCA (nLCA) method to provide combined life cycle-based nutritional and environmental information to consumers and facilitate food consumption decisions at the meal level. The following sections have been published as a journal paper titled “Majumdar, S., McLaren S.J., van der Pols, J.C., and Lister, C.E. (2024). An nLCA approach to support consumer meal decisions: a New Zealand case study of toppings on toast. *Frontiers in Sustainable Food Systems*. 8:1363565. <https://doi.org/10.3389/fsufs.2024.1363565>

Abstract

Introduction: This study investigates the development and potential application of a nutritional Life Cycle Assessment (nLCA) method to rank meals, using a case study of a “toppings on toast” (ToTs) meal. Methodological issues are investigated in the context of application to support consumers to make more informed food choices at the meal level.

Methods: Fourteen selected ‘toppings on toast’ (ToTs) commonly consumed in New Zealand were evaluated for their climate change impacts and nutritional value using the serve size of each topping as the functional unit (FU). New Zealand-specific climate change values were obtained from an existing database and recent literature. Nutritional value was calculated using the NRF family of indices – specifically the NRF_{9,3} and NRF_{28,3} indices (the latter constructed for this study to include all nutrients in the selected toppings for which reference values were available) and presented in a separate midpoint nutrition impact category. The NRF and climate change scores were assigned quartile-based weights, and the weight of each index score was averaged with that of the climate change score. Based on these average values, the toppings were ranked in two ranking sets (one for each index). In a sensitivity analysis, two alternative

reference units were also used (100 g and 100 kcal) to investigate how different FUs influenced the final rankings.

Results: The results showed that use of one or other NRF index affected the magnitude of the nLCA results; however, the rankings of the ToTs based on the nLCA results did not change much between the two indices. Avocado and peanut butter performed the best (top two ranks), and bacon, butter, and cheese were the poorest performers (bottom two ranks), for both the ranking sets. The toppings which did change ranks mostly moved up or down by only one position. Thus, the results of this case study suggest that the NRF_{9.3} index is sufficient to determine overall the best, medium, and worst performing toppings in the ToT meal context. However, the results also showed that water-soluble vitamins and unsaturated fats included in the NRF_{28.3} index contributed significantly to the nutritional scores for most of the toppings and were instrumental in the rank changes for the toppings which are particularly rich in these nutrients.

Conclusion: Thus, for a more diverse range of toppings/meals, an expanded index including these nutrients can generate more nuanced rankings. This study contributes to the nascent but fast-growing nLCA research field, particularly within the meal context. The method used in this case study could be applied in food composition databases, restaurant menus, and websites/apps that provides recipes for meals. However, the study also highlighted the potentially significant variability in climate change and nutritional values in the toppings associated with different production practices, seasonality, and different varieties of the same product. Any future development of nLCA-based meal level rankings should address this variability and communicate it to the consumer.

5.1 Introduction

Agri-food systems have far-reaching environmental impacts, including significant contributions to climate change, biodiversity loss, freshwater use and pollution, and soil degradation (Crippa et al., 2021; Dudley and Alexander, 2017; Food and Agriculture Organization of the United Nations (FAO), 2020; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem

Services, 2019; Mekonnen and Hoekstra, 2014; Springmann et al., 2018a; Vermeulen et al., 2012). At the same time, much of the world's population has nutrient-poor diets low in fresh fruits, vegetables, grains and legumes, and overconsumption of foods that increase risk of chronic disease, e.g. processed and ultra-processed foods high in sodium, saturated/trans fats, and added sugar (Clark et al., 2019; Global Nutrition Report, 2021; Springmann et al., 2018b). There are 690 million undernourished people and 11 million deaths related to poor diets around the world annually (Global Panel for Agriculture and Food Systems for Nutrition, 2020). With a global population set to peak at almost 10 billion by 2050 (Gu et al., 2021), this 'diet-environment-health trilemma' of global food systems (Clark et al., 2018; Sabaté, 2019) requires urgent attention, and has led to calls for a transition to more sustainable food systems (Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO), 2019; Global Panel for Agriculture and Food Systems for Nutrition, 2020; United Nations Framework Convention on Climate Change (UNFCCC), 2023b; Willett et al., 2019). From a demand constraint perspective, the focus has been on changes in consumption patterns and dietary shifts (Heller et al., 2013; Meier and Christen, 2013; Hallström et al., 2015; Notarnicola et al., 2017; Willett et al., 2019). However, at the same time there are concerns about the nutritional inadequacy of some diets (vegan, vegetarian etc.) that have been widely acknowledged as being good for planetary health (Graham et al., 2019; Mazac et al., 2023). Consumers can be supported in their choices for healthy and sustainable foods by having access to easily comprehensible information about a food product's environmental and nutritional credentials in the form of indicators and other metrics (Notarnicola et al., 2015, 2017).

Environmental LCA has been widely used for assessment of the environmental impacts of production and/or packaging, distribution, and consumption of various agri-food products (Clark et al., 2022; Schaubroeck et al., 2018), meals/menus (Calderón et al., 2018; Takacs et al., 2022) and diets (Eme et al., 2019; Hallström et al., 2015; Henriksson et al., 2021). It is recognized as one of the most informative and holistic methods to evaluate environmental impacts associated with agri-food systems (McAuliffe et al., 2018; Sala et al., 2017). The unit of

analysis in an LCA is the FU, representing the function or service provided by a product system. Food LCAs have traditionally mostly used mass- or volume-based FUs, and do not account for nutritional value (Saarinen et al., 2017; Sala et al., 2017; Sonesson et al., 2017). Yet one of the most critical functions of food is to provide nutrition to support healthy growth, development, and longevity (Willett et al., 2019; World Health Organization (WHO), 2023). This has led to development of a nascent field of study on nutritional LCA (nLCA), defined as an LCA study in which nutrition is considered the main, or one of the main, functions of food (McLaren et al., 2021).

Several nLCA studies assess the quantity (or quality-corrected quantity) of selected individual nutrients in food items and diets, including phenols, protein, fat, calcium, and energy (e.g. Berardy et al., 2019; Martínez-Blanco et al., 2011; McAuliffe et al., 2018; Oonincx and de Boer, 2012; Saarinen et al., 2017; Salazar et al., 2019). However, foods are a complex mix of many macro- and micro-nutrients that are essential for the proper functioning of the human body. Nutritional Profiling (NP) can be used to assess the nutritional value of foods more comprehensively (Drewnowski et al., 2019, 2021). In this approach, the nutritional value is expressed in the form of indices featuring nutrients to encourage, nutrients to limit, and/or a combination of both.

One particular set of indices, the Nutrient Rich Food (NRF) family of indices proposed by Drewnowski (2009) has been comprehensively tested and validated and is increasingly used in nLCA studies (see for example, Aceves-Martins et al., 2022; Bianchi et al., 2020; Doran-Browne et al., 2015; Esteve-Llorens et al., 2019; Green et al., 2020, 2021; Hallström et al., 2019; Mazac et al., 2023; Ridoutt, 2021; Strid et al., 2021; Van Kernebeek et al., 2014). An NRF index is comprised of two indices; one represents nutrients to encourage (NR_e) and the other represents

nutrients to avoid or limit (LIM)³⁸. An NRF index is commonly calculated as the difference between the NR_n and LIM indices. This NRF family of indices can include a variable number of nutrients and can be calculated using nutrient reference values for specific population groups, thus it is easily adapted to suit the requirements of a particular nLCA study. Several methodological choices have to be made when choosing to use an NRF (or other NP) index. These include the number of nutrients to assess, whether a specific index is chosen for each food group or whether one index is used for all food groups considered in the analysis, the reference amount to be used (e.g. mass-, energy- or serve size-based), capping/weighting the nutrients, and energy standardization (Bianchi et al., 2020; Drewnowski, 2017; Green et al., 2021, 2023; Hallström et al., 2019; Kyttä et al., 2023; Masset et al., 2015; Saarinen et al., 2017; Scarborough et al., 2010; Strid et al., 2021). Green et al. (2020) note that methodological choices with respect to these variables can significantly alter the assessment of nutritional value of a particular food. However, there is no formal consensus on how to choose the best index-based metric to summarize this nutritional value. Moreover, case studies investigating the influence of these methodological choices in the context of nLCA studies are currently limited (see, for example, Bianchi et al., 2020).

Regarding the selection of nutrients, an index with a limited number of nutrients is sometimes considered most appropriate for nutrient profiling (Drewnowski, 2017; Fulgoni et al., 2009; Green et al., 2020; Weidema and Stylianou, 2020). However, selection of nutrients for nutritional index development should be based on sound justification (Bianchi et al., 2020; Hallström et al., 2019; Ridoutt, 2021; Strid et al., 2021) due to the risk of excluding nutrients that may have an important role to play in human health. The $NRF_{9.3}$ index, comprising nine nutrients to encourage (protein, fibre, calcium, iron, magnesium, potassium, and vitamins A, C, and E) and

³⁸ The NR_n index is calculated as the sum or mean of the ratio of beneficial/qualifying nutrients relative to their associated reference values (e.g. Recommended Dietary Intake, RDI). The LIM index is expressed as the sum or mean of the ratio of disqualifying nutrients to their associated reference values (e.g. Upper Limit (UL) of intake).

three nutrients to limit (added sugar, sodium, and saturated fats), is the most widely used and validated NRF index to date (Doran-Browne et al., 2015; Fernández-Ríos et al., 2021; Van Kernebeek et al., 2014). However, the NRF_{9.3} index does not reflect the full nutritional value of a food, and this is particularly relevant for food items with specific characteristics (Bianchi et al., 2020; Kägi et al., 2012). For example, seafoods such as tuna and salmon are a rich source of Polyunsaturated Fats (PUFAs) (Coelho et al., 2016; Salazar et al., 2019), avocados are a good source of Monounsaturated Fats (MUFAs) (Guan et al., 2022), mushrooms are rich in selenium (Falandysz, 2008), and chicken is a good source of selenium and B vitamins like niacin and vitamin B6 (New Zealand Food Composition Database (NZFCD), 2022). However, none of these nutrients are included in the NRF_{9.3} index. In such cases, Bianchi et al. (2020) suggest that an index with a more comprehensive selection of nutrients to encourage, and/or one which is tailored to represent the nutritional profile of the foods being studied, may be more appropriate. For example, Hallström et al. (2019) and Saarinen et al. (2017) developed expanded indices to include all nutrients relevant to the food group being studied. Likewise, Vieux et al. (2013) included all nutrients they considered 'key' for diet-related assessments. Another approach is to include all nutrients with formally available Daily Recommended Intake (DRI) and nutrient composition values (Fern et al., 2015; Green et al., 2021, 2023; Ridoutt, 2021).

Combined nutritional and environmental LCA studies have mostly focused on individual food items or diets; there have been relatively fewer combined studies at the meal level. Of these, several studies considered meals based on, or aligned to dietary guidelines, nutritional recommendations (e.g. configuring meals to the Lunch Plate model), or national certification standards for 'healthy meals' (García-Herrero et al., 2019; Saarinen et al., 2012; Sameshima et al., 2023; Virtanen et al., 2011). Some studies assumed that the meals being considered are nutritionally adequate (Takacs et al., 2022), while others scaled the meals to have comparable nutritional and/or caloric values, or to similar quantities of foods (Davis et al., 2010; Ernstoff et al., 2019; Sameshima et al., 2023; Virtanen et al., 2011). Thus, these studies did not compare

meals based on their individual calculated nutritional value; rather, the latter was kept constant, and the environmental impacts of these nutritionally comparable meals were assessed.

A review of the literature enabled the identification of 11 meal-level studies relevant to this research paper, i.e. meal-level nLCA studies as well as meal-level studies that used environmental and nutritional information to rank meals. Appendix E, Table E1 shows that most of the identified studies used integrated methods of analysis³⁹. This is related to a common theme in the literature – the discussion around ‘single scores’ representing the combined assessment of both environmental impacts and nutrition to facilitate informed consumer choices (Lukas et al., 2016; Mazac et al., 2023; Schaubroeck et al., 2018; Sturtewagen et al., 2016). Around half of the studies included ranking of meals based on their combined environmental impacts and nutritional value, and a variety of approaches were used to determine the nutritional value of meals. Environmental impacts were assessed in various impact categories, with climate change impacts assessed most frequently. Most of the 11 studies assessed actual meals or meals constructed with real-life data, in university, school, and worksite canteens, care homes, and restaurants (Appendix E, Table E1), while only three studies (Batlle-Bayer et al., 2020; Lukas et al., 2016; and Mazac et al., 2023) evaluated theoretical/hypothetical meals. In fact, the importance of using real-life meals to account for social/cultural acceptance was noted for future research (e.g. Batlle-Bayer et al., 2020).

In summary, the literature showed that the integrated approach to combined assessments was the more frequently adopted approach in meal-level studies, and a ‘real life’ meal focus was considered important to the analyses. Moreover, only four nLCA studies were identified that used nutritional indices to compare and rank meals. Three of these studies used the NRF_{9,3}

³⁹ In combined environmental and nutritional assessments such as nLCA studies, these two aspects can be assessed in parallel or in an integrated single score approach. With respect to integrated assessments in nLCA studies, the environmental impact of food is calculated relative to a unit of its nutritional value (e.g. Berardy et al., 2019; Chapa et al., 2020; Doran-Browne et al., 2015; González-García et al., 2018; Green et al., 2021; Strid et al., 2021).

index, and only Mazac et al. (2023) used the NRF approach with more than 9 nutrients to encourage. Therefore, given the outstanding methodological issues related to the use of NRF indices in nLCA studies, this research strives to develop a better understanding of the use of NRF indices in nLCA studies of meals. To do this, different methods were investigated for ranking foods within a simple meal context, using a case study of a New Zealand-specific ‘toppings on toast’ (ToTs) meal. The overarching aim of this study is to understand how nLCA can be used to support consumers to make informed food choices based on credible, life cycle-based nutritional and environmental information.

5.2 Method

A survey was conducted to identify common food choice preferences for ToT meals (Section 5.2.1). The survey results were used to identify the most commonly consumed toast toppings. For the selected toppings, climate change impact scores (Section 5.2.2), nutritional value scores (Section 5.2.3.3), and nLCA results (Section 5.2.3.4) were then calculated.

5.2.1 Survey of preferred toast toppings

A survey was developed as an online questionnaire using Google Forms, with questions about topping preferences on toast. It was shared with the researchers’ personal and professional contacts by email and on social media. Of the 157 respondents, 94% said that they commonly consume toasted or untoasted bread with toppings as a meal or snack option and most respondents preferred to have this for breakfast or lunch. Most of the respondents were fairly evenly distributed between age groups covering 21–60-year-old people, with a smaller proportion aged younger than 20 or over 60 years of age – thus, the survey was fairly representative of the age distribution of adult New Zealand residents (O’Neill, 2023). Respondents indicated that the most preferred toppings were avocado, tomatoes, cheddar cheese, salmon, tuna, chicken, egg, butter, hummus, mushrooms, banana, honey, jam, nut butters,

marmite/vegemite⁴⁰, and bacon. Of these, LCA data was not available for hummus and marmite/vegemite, therefore these specific toppings were excluded from further analysis.

5.2.2 Climate change scores

The literature on the nutrition-environment nexus and sustainable diets notes a consistent focus on climate change as the priority environmental impact category of interest (Eme et al., 2019; Guo et al., 2022; Hallström et al., 2015; Harrison et al., 2022; Heller et al., 2013; Jones et al., 2016). Given the current climate crisis (United Nations Framework Convention on Climate Change (UNFCCC), 2023a), climate change was considered for the environmental impact analysis. The impact scores, calculated using Global Warming Potential (GWP) over a 100-year timeframe (GWP100), were quantified for each of the selected toppings.

In a recent study, Drew et al. (2020) developed an New Zealand-specific database of LCA-based climate change impact scores for a comprehensive range of food products aligned with those listed in the New Zealand Food Composition Database. To do this, the authors first screened several available databases based on predefined criteria and then selected the one provided by Hoolohan et al. (2013) as the reference database that matched all the criteria (see Drew et al. (2020) for details on inclusion and exclusion criteria). New Zealand-specific LCA data was available for the production of some food products; for these products, the farming/processing-related climate change values were used in the new database (for example, tomatoes, wine, cheese, and dairy milk). For other domestically grown food items for which climate change values were unavailable, GHG emissions were estimated by averaging New Zealand-specific farming/processing values of similar food items grown in New Zealand for which values were available. In cases where this was not possible, the value from the reference database (Hoolohan et al., 2013) was used as a proxy. One exception to this rule was dairy products. For some dairy

⁴⁰ Yeast spreads commonly consumed in the UK and Commonwealth countries, particularly Australia and New Zealand (Rozin and Siegal, 2003; Vriesekoop et al., 2022).

products which did not have associated New Zealand-specific emissions data, emission values for the same dairy products in the reference database were adapted to reflect the quantity of New Zealand dairy milk used in them. The dairy milk emissions estimates in the reference database were based on global data obtained from (Food and Agriculture Organization of the United Nations (FAO), 2010). For all the products for which post-production GHG emissions data were unavailable for New Zealand, values in the reference database were adapted to reflect transport, storage, and distribution within New Zealand to the point-of-sale. To our knowledge, this is the only comprehensive New Zealand-specific LCA-based GHG emissions database available currently.

Because the Hoolohan et al. (2013) dataset (used to develop the Drew et al. (2020) dataset) is ten years old and uses LCA values from even earlier years, a decision tree approach was applied to arrive at the most representative and relevant climate change values for the food items selected for this study. Such decision trees have also been used in other areas of quantitative and qualitative research (e.g. De Smalen et al., 2021; Dutton et al., 2015; Verdinelli & Scagnoli, 2013). As shown in Figure 5.1, the starting point for the decision flowchart was the availability of recent (<5 years old) climate change impact scores for food items that are specific to New Zealand. The resulting climate change scores for the chosen toast topping, including further details on calculations, are listed in Appendix E, Table E2.

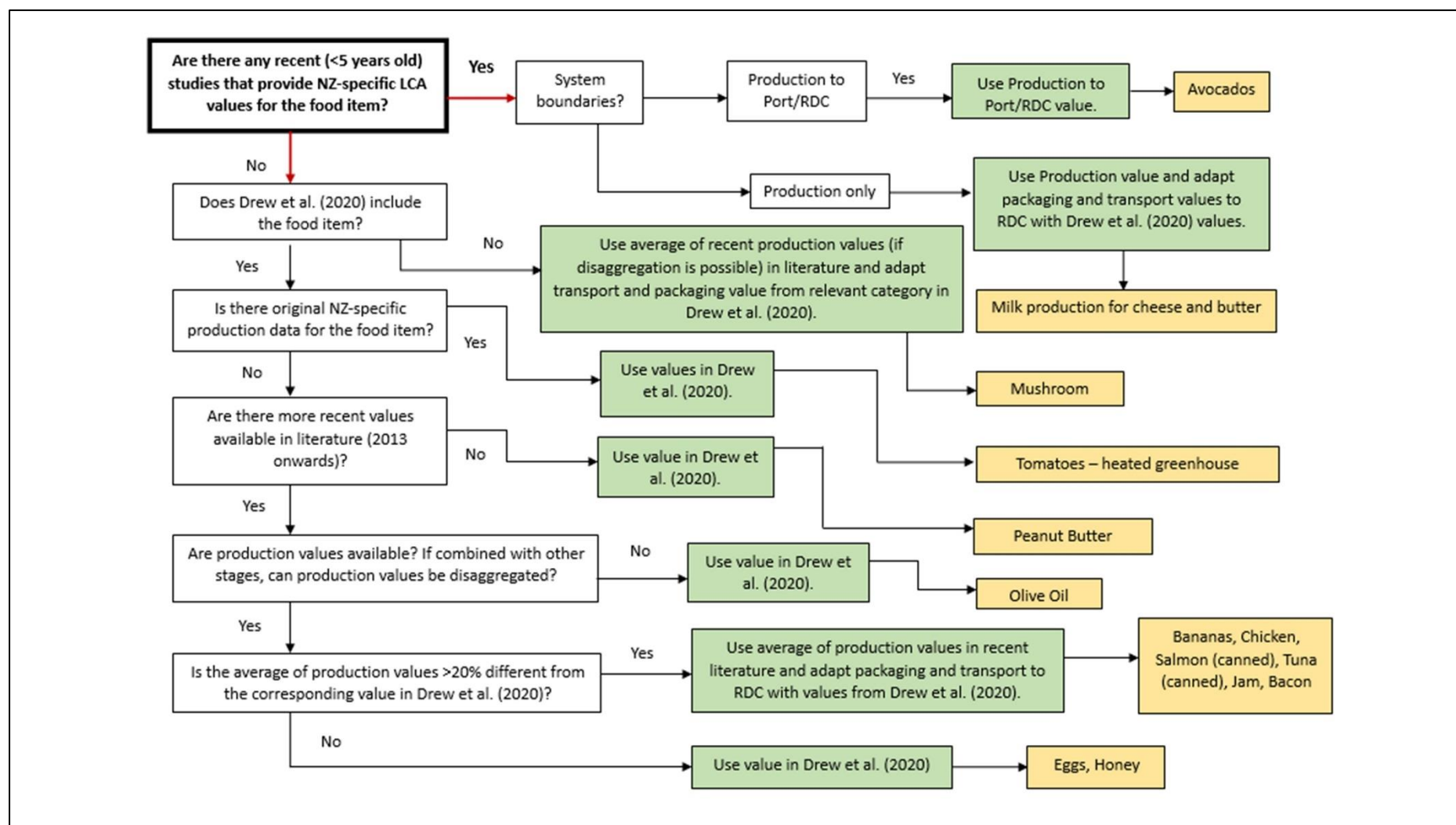


Figure 5.1 Decision tree to identify the climate change impact scores for the toast toppings selected for this study

5.2.3 Nutritional values

5.2.3.1 Assignment to food group

The food group categorizations used in this study are listed in the Eating and Activity Guidelines published by the New Zealand Ministry of Health (2020) (see Appendix E, Table E2 for a list of all toppings with the food groups they belong to in this study)⁴¹. These dietary guidelines indicate that processed foods typically high in sugar, saturated/trans fats, and/or salt (e.g. processed meat, cakes, biscuits, butter, honey and jam) should be replaced with nutrient-rich and less processed foods. The New Zealand dietary guidelines do not categorize these foods separately, but the Australian dietary guidelines suggest a separate category for them called ‘discretionary foods’ (National Health and Medical Research Council, 2013a). Therefore, for this study, four toppings (bacon, butter, jam, and honey) were categorized as ‘discretionary foods’.

5.2.3.2 Nutritional score

Reference Unit

This study considers different food items in a simple meal context; therefore, the portion size (which in most cases was the serve size⁴²) of individual toppings was selected as the appropriate reference unit (Green et al., 2023; McLaren et al., 2021). Serve sizes for most of the toppings in this study were obtained from the standard values provided in the New Zealand Food Composition Database (NZFCD) (2022) (see Appendix E, Table E3 for all serve sizes used in this study). For some of the toppings, adjustments were made so that the assumed amount consumed was more realistic (for example, two rashers of bacon instead of one) guided by the

⁴¹ The fourth group in the guidelines is ‘Grains - Grains (bread, rice, pasta, cereals), which in this study is toast and remains constant throughout the study.

⁴² The terms ‘serve size’ and ‘portion size’ are sometimes used interchangeably in literature to represent the quantity of food typically consumed by an individual, however they mean different things (Spanos et al., 2015). Serve size refers to the quantified (measured) value of a food product found on nutrition labels (National Heart Lung and Blood Institute, 2023), whereas portion size refers to the actual quantity that an individual consumes in one sitting for a meal or snack (The Academy of Nutrition and Dietetics, 2023).

New Zealand and Australian dietary guidelines (Ministry of Health, 2020; National Health and Medical Research Council, 2013b).

Choice of Nutrients in Indices

The number and type of nutrients included in published nutritional indices varies from 6 to 22 qualifying, and up to three disqualifying nutrients in NRF indices, and up to 27 qualifying and 6 disqualifying nutrients in indices using the Nutrient Balance Concept (NBC) (see Appendix E, Table E4). For this study, it was decided to use the NRF family of indices and NRF_{9.3} was chosen as the baseline since it is the most widely used index. However, as discussed in Section 5.1, NRF_{9.3} includes a limited number of nutrients that don't represent the entire nutritional quality of all foods. Therefore, a more comprehensive nutritional index was compiled that included all the nutrients which appear at least once in the New Zealand Food Composition Database nutritional composition data for each of the 14 toppings, and for which Nutrient Reference Values (NRVs)⁴³ are also available⁴⁴. This resulted in an index with 28 nutrients to encourage and 3 nutrients to limit. The selected nutrients in both indices are listed in Table 5.1.

NRVs for each nutrient were obtained from the combined NRV list developed for Australia and New Zealand by the National Medical Health and Research Council (2017). Some NRVs vary by

⁴³ Nutrient Reference Values (NRVs) are a set of population-level nutrient intake benchmarks established by health authorities. They include both Recommended Dietary Intakes (RDI) and tolerable Upper Intake Levels (UL). RDI refers to the average daily dietary intake level that is sufficient to meet the nutrient requirements of nearly all (97–98%) healthy individuals in a particular life stage and gender group. UL refers to the highest average daily nutrient intake level likely to pose no adverse health effects to almost all individuals in the general population. In this study, RDI values are used as reference points for qualifying nutrients, while UL values are used as reference thresholds for nutrients to limit within the NRF framework.

⁴⁴ Biotin, molybdenum, and fluoride were excluded as there were no values available for these in the food composition data of the 14 toppings. Published NRVs were unavailable for chloride and sulphur. Some bioactive phytochemicals, like flavonoids and carotenoids, and food additives were excluded from the study because of lack of both available NRVs and standardized composition data.

age and sex and so the mean NRVs for adult men and women (based on the 50:50 ratio of men: women (as per Stats NZ, 2023) in the New Zealand population were used in the analysis. The NRV value for MUFAs was obtained from Drewnowski et al. (2009) (which provided the MUFA value for a 2000 kcal diet) and adapted to the standard New Zealand diet of 2081 kcal as per the Australia New Zealand Food Standards Code (Food Standards Australia New Zealand (FSANZ), 2021). The Upper Levels (ULs) of intake for saturated fats and sodium were also obtained from Food Standards Australia New Zealand (FSANZ) (2021). The UL for added sugar was adapted to the New Zealand 2081 kcal diet from the value provided for an average 2000 kcal diet in Fulgoni et al. (2009). Weighting and/or capping were not applied to the indices (see Section 5.4.1.3 for a discussion on this methodological choice).

Table 5.1 Nutrients included in the two nutrient indices used in this study

Category	Nutrient	NRF _{9.3}	NRF _{28.3}	NRV	NRV unit
Macronutrients	Dietary fibre	✓	✓	28	g
	Protein	✓	✓	59	g
	Monounsaturated fatty acids (MUFAs)		✓	21	g
	Polyunsaturated fatty acids (PUFAs) – Omega 3		✓	1.1	g
	PUFAs – Omega 6		✓	11	g
Minerals	Calcium	✓	✓	1129	mg
	Chromium		✓	30	µg
	Copper		✓	1	mg
	Iodine		✓	150	µg
	Iron	✓	✓	10	mg
	Magnesium	✓	✓	368	mg
	Manganese		✓	5250	µg
	Potassium	✓	✓	1000	mg
	Phosphorous		✓	3300	mg
	Selenium		✓	65	µg
	Zinc		✓	11	mg
Vitamins	Folate		✓	400	µg

	Niacin		✓	15	mg
	Pantothenic acid		✓	5	mg
	Riboflavin		✓	1	mg
	Thiamin		✓	1	mg
	Vitamin B12		✓	2	µg
	Vitamin B6		✓	1	mg
	Vitamin C	✓	✓	45	mg
	Vitamin A	✓	✓	800	µg
	Vitamin D		✓	9.3	µg
	Vitamin E	✓	✓	8.5	mg
	Vitamin K		✓	65	µg
Nutrients to limit	Added sugar	✓	✓	52	g
	Saturated fat	✓	✓	24	g
	Sodium	✓	✓	2300	g

5.2.3.3 Calculation of nutritional value

All nutritional composition data were obtained from the New Zealand Food Composition Database (NZFCD) (2022). This database considers the sugar content in honey to be both added and free, based on the definition of the two kinds of sugars provided by the United States Food and Drug Administration (Erickson and Slavin, 2015) and the World Health Organization (WHO) (2015). Since honey was studied as a topping/food item (and not as a sweetener) in this study, the sugar content in honey was not considered to be added sugar.

For each topping, the ratio of every nutrient to its NRV was calculated. These ratios can then either be summed, or their mean calculated, to arrive at the NR_n or LIM score. For this study, the NR_n and LIM values were calculated using the mean method (see Eqs. 1 and 2) since the toppings were being evaluated for comparison using two different indices with a different number of nutrients considered in each index. The NRF value was obtained by subtracting the LIM from the NR_n .

$$NR_n = 1/n \times \sum_{i=1}^n \left(\frac{Nutrient_i}{NRV_i} \right) \quad \dots \text{Eq. 1}$$

n = number of beneficial/qualifying nutrients; $Nutrient_i$ = content of beneficial/qualifying nutrient 'i' per serve of the topping (g, mg, or μg); NRV_i = the nutrient reference value of beneficial/qualifying nutrient 'i' (g, mg, or μg)

And

$$LIM = 1/3 \times \sum_{j=1}^3 \left(\frac{Nutrient_j}{NR_j} \right) \quad \dots \text{Eq. 2}$$

$Nutrient_j$ = content of limiting/disqualifying nutrient per serve of the topping (g or mg); NR_j = the nutrient reference value of limiting/disqualifying nutrient 'j' (g or mg)

5.2.3.4 Calculation of nLCA results

For the combined nutritional and environmental analysis (nLCA), the climate change impact scores and nutritional (NR_n , LIM, and NRF) scores per serve size were compiled into one table for the 14 toppings. In addition, these scores were also presented on the basis of the Energy Density (ED) of the food items per serve as recommended in McLaren et al. (2021, Figure 6). The scores for all the toppings within each category (climate change impact, NR_9 , NR_{28} , $NRF_{9.3}$, $NRF_{28.3}$, and ED) were divided into quartiles and each quartile assigned a color for a visual representation of the nLCA results. In a next step, the climate change impact, $NRF_{9.3}$ and $NRF_{28.3}$ scores of all the toppings were assigned performance-based values from 1 (worst performance) to 4 (best performance), based on the quartiles. Then two scenarios were established – ranking set A and ranking set B. Set A consisted of the average of the above-mentioned assigned values for climate change and $NRF_{9.3}$ for each of the 14 toppings. Set B used the assigned values for climate change and $NRF_{28.3}$ instead of $NRF_{9.3}$ (See Eqs. 3 and 4). The toppings were then ranked based on the values obtained in these two scenarios.

$$RA_{score} = (V_{cc} + V_{9.3})/2 \quad \dots \text{Eq. 3}$$

RA_{score} = ranking score for the topping for ranking set A; V_{cc} = quartile-based value assigned to the topping for its climate change score; $V_{9.3}$ = quartile-based value assigned to the topping for its $NRF_{9.3}$ score

And

$$RB_{score} = (V_{cc} + V_{28.3})/2 \quad \dots \text{Eq. 4}$$

RB_{score} = ranking score for the topping for ranking set B; V_{cc} = the quartile-based value assigned to the topping for its climate change score; $V_{28.3}$ = quartile-based value assigned to the topping for its $NRF_{28.3}$ score

In addition, a sensitivity analysis was undertaken using the two other commonly used reference units, mass (per 100 g) and energy (per 100 kcal), using the same method described above.

5.3 Results

The climate change, nutritional and nLCA results are presented in this section per serve size for the baseline scenario, followed by a comparison of the results when using a mass- or energy-based reference/functional unit.

5.3.1 Baseline results

5.3.1.1 *Climate change impact scores*

Figure 5.2 shows that the climate change impact scores are higher for the toppings that are products from animals rather than plants; canned salmon has the highest impact score with 0.42 kg CO₂ eq./serve, followed closely by bacon, cheddar cheese, tuna, and chicken. Avocados and bananas had the lowest impact scores among the fresh plant-based foods with 0.07 and 0.10 kg CO₂ eq./serve respectively. Jam and honey (0.04 kg CO₂ eq./serve each) had the lowest climate change impacts of all the 14 toppings.

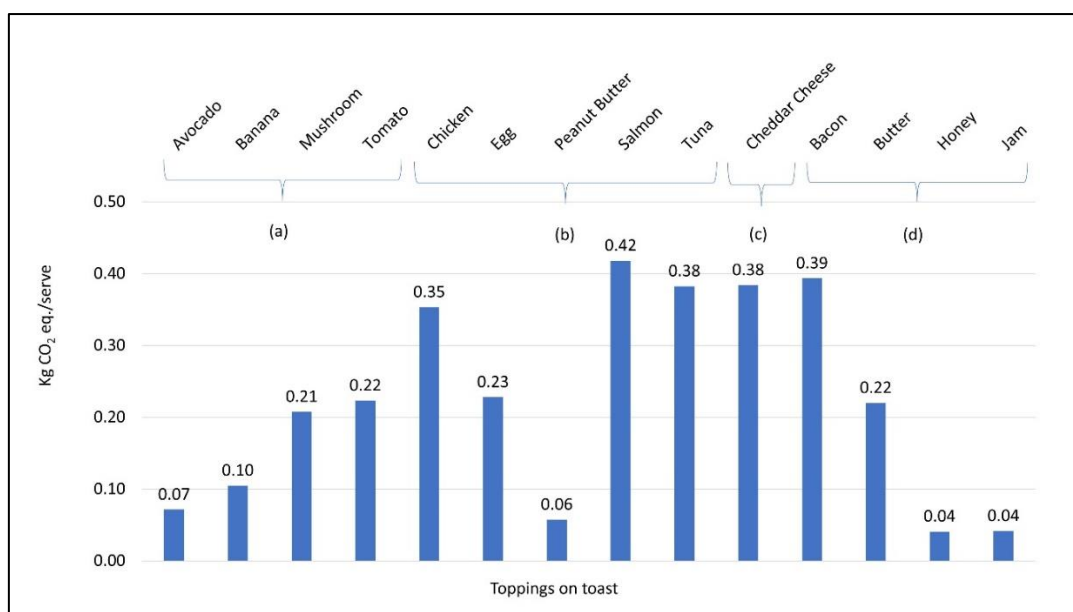


Figure 5.2 Climate change impact scores (kg CO₂ eq./serve) for each of the 14 selected toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods

5.3.1.2 Nutritional analysis

The NR_n and LIM scores are shown in Figure 5.3. Butter had the highest LIM score (0.33), followed by bacon (0.25) and cheddar cheese (0.17). When considering the NR₉ index, chicken and honey had the highest (0.1) and lowest (0.001) scores respectively; for the NR₂₈ index, tuna and salmon had the highest scores (0.18 and 0.17 respectively) and jam the lowest score (0.002).

The NR₂₈ scores were higher than the NR₉ ones for most of the toppings. The largest change (%) from the NR₉ to NR₂₈ score was noted in tuna (nearly 200% higher) (Figure 5.4). This was followed by salmon, bacon, honey, and mushrooms – all of which showed >100% increase from the NR₉ score. The exceptions to this trend were tomatoes, bananas, cheddar cheese, and jam. The lower NR₂₈ scores (relative to NR₉) for these four toppings can be attributed to the presence of relatively smaller quantities of other nutrients (not included in NR₉), which reduced the mean value of the nutrient to NRV ratios used to calculate the NR_n indices. To illustrate, the largest increase from NR₉ to NR₂₈ scores was noted for tuna (as mentioned above) and the largest decrease for tomato. For tuna, the nutrients common to both indices contributed only 11% to

the total NR_{28} score; for tomato, 66% of the contribution to the total NR_{28} score was from the common nutrients (see Appendix E, Table E5).

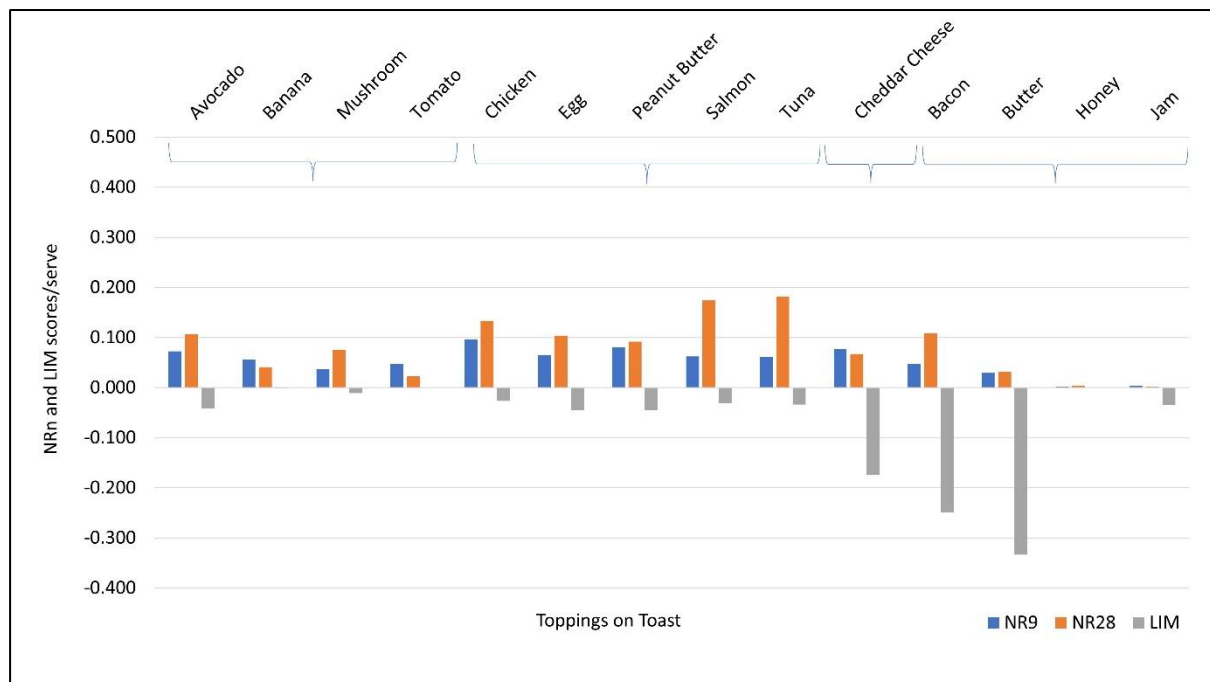


Figure 5.3 NR_n and LIM values for 9 and 28 qualifying and 3 disqualifying nutrients for each of the 14 toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

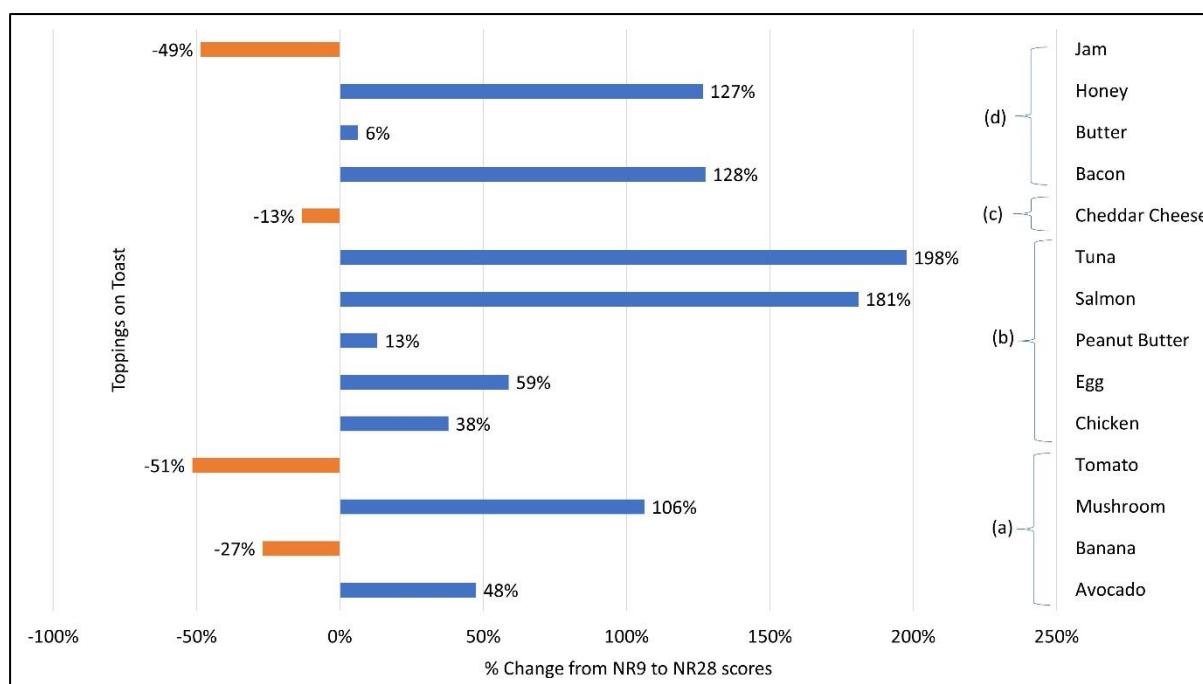


Figure 5.4 Change (%) from NR_9 to NR_{28} scores of the 14 toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

The overall trend of the majority of the toppings displaying higher NR_{28} scores compared to NR_9 can be attributed to the inclusion of a larger number of water-soluble vitamins (as well as minerals and unsaturated fats to a lesser extent) in the NR_{28} index (see contribution analysis in figures 5.5 and 5.6). Minerals, fat-soluble vitamins, and proteins were the main contributors to the NR_9 score of most of the toppings (accounting for 38%, 23%, and 22% to the total score on average), with water-soluble vitamins accounting for only 9% of the total score on average. There was no contribution of dietary fibre to the total NR_9 scores of the animal-based toppings, but it accounted for 9-24% of the total NR_9 score for all the plant-based toppings, with the highest contribution in avocados (24%). However, when using the NR_{28} index, the average contribution of water-soluble vitamins to the total NR_{28} score increased to 39%, while the average contribution of fat-soluble vitamins and proteins dropped to 10% and 4% of the total score respectively. Mineral contribution also decreased, but to a lesser extent (28% of total), while unsaturated fat, now represented in the NR_{28} index, accounted for 17% of the total score on average. Average dietary fibre contribution was the lowest at 3% of the total NR_{28} score.

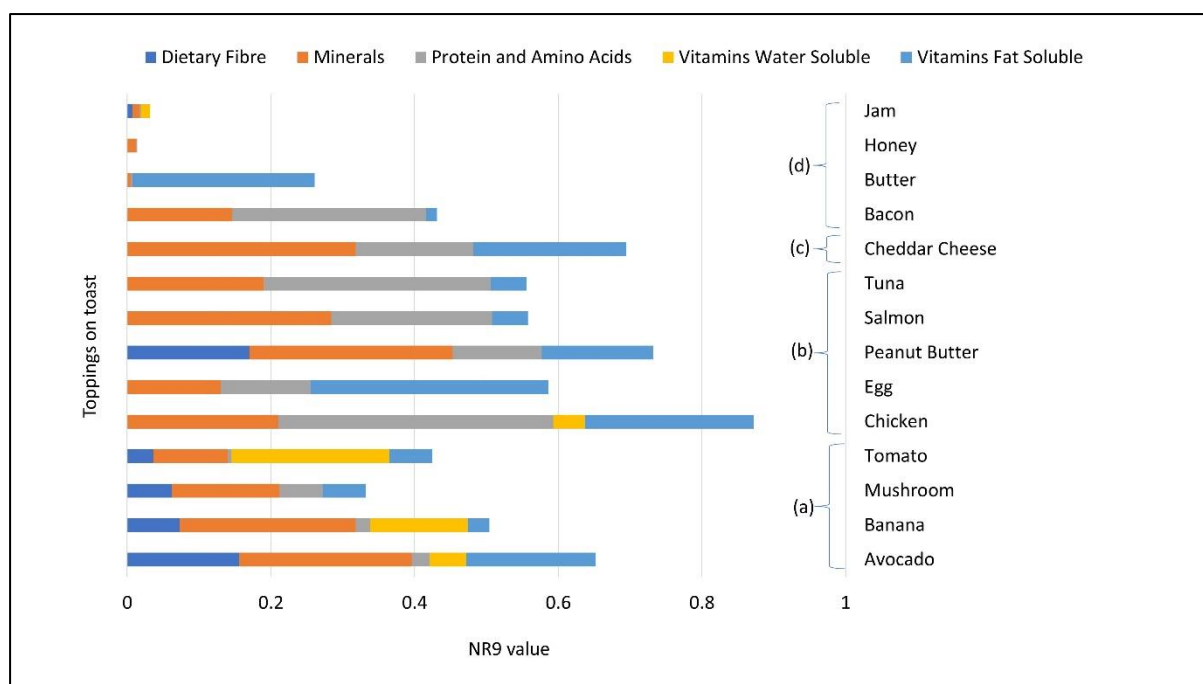


Figure 5.5 Contribution of nutrient categories to NR₉ values for each of the 14 selected toast toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

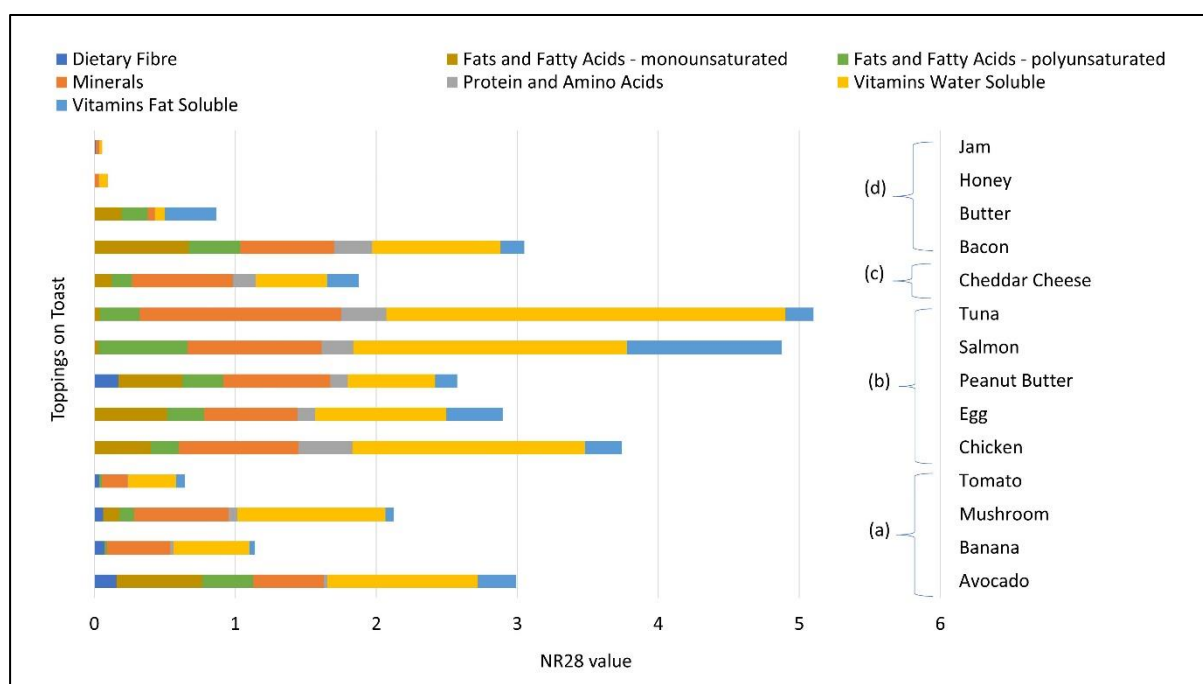


Figure 5.6 Contribution of nutrient categories to the NR₂₈ values for each of the 14 selected toast toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

With respect to the three toppings with the largest LIM scores (bacon, butter, and cheese), sodium was the main contributor to the LIM score for bacon (70%), while saturated fatty acids contributed the most to the LIM scores for butter and cheese (95% and 75% respectively) (Figure 5.7). Added sugar was present in only one topping (jam) and accounted for almost its entire LIM value.

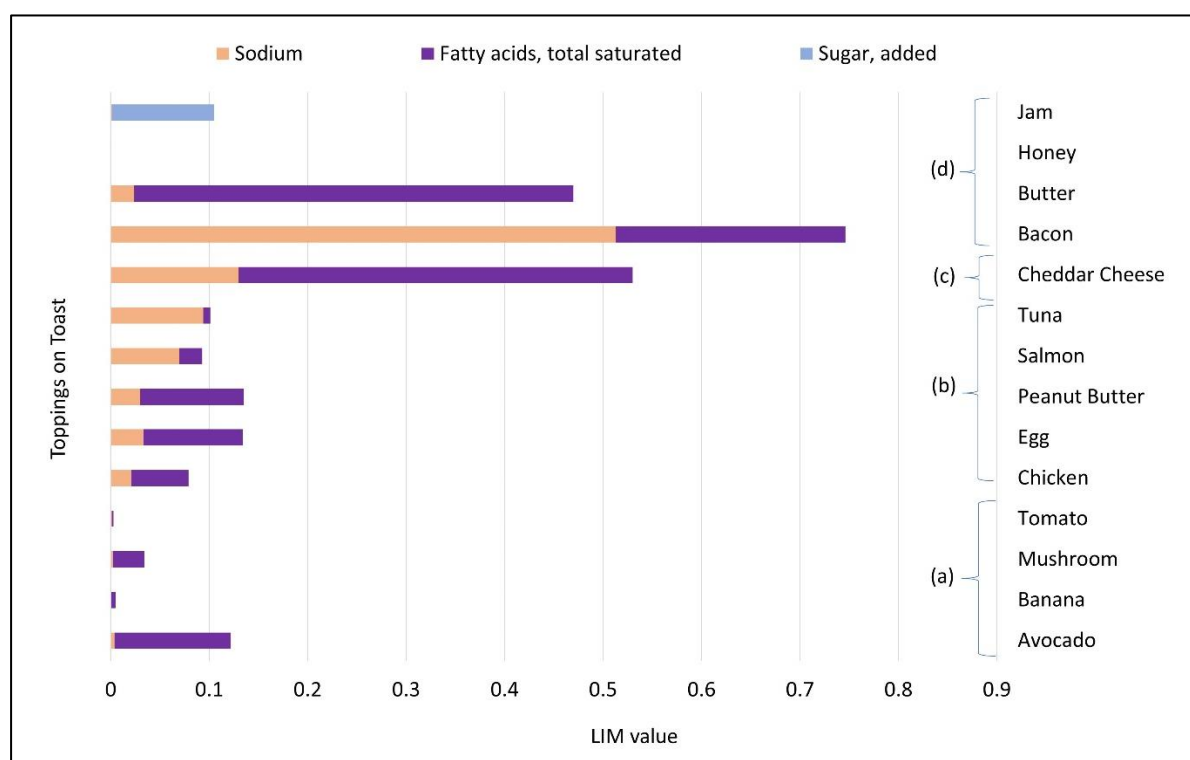


Figure 5.7 Contribution of the three disqualifying nutrients to the LIM scores for each of the 14 selected toast toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

Butter, bacon, cheddar cheese and jam had negative scores for both the $\text{NRF}_{9.3}$ and $\text{NRF}_{28.3}$ indices (Figure 5.8).

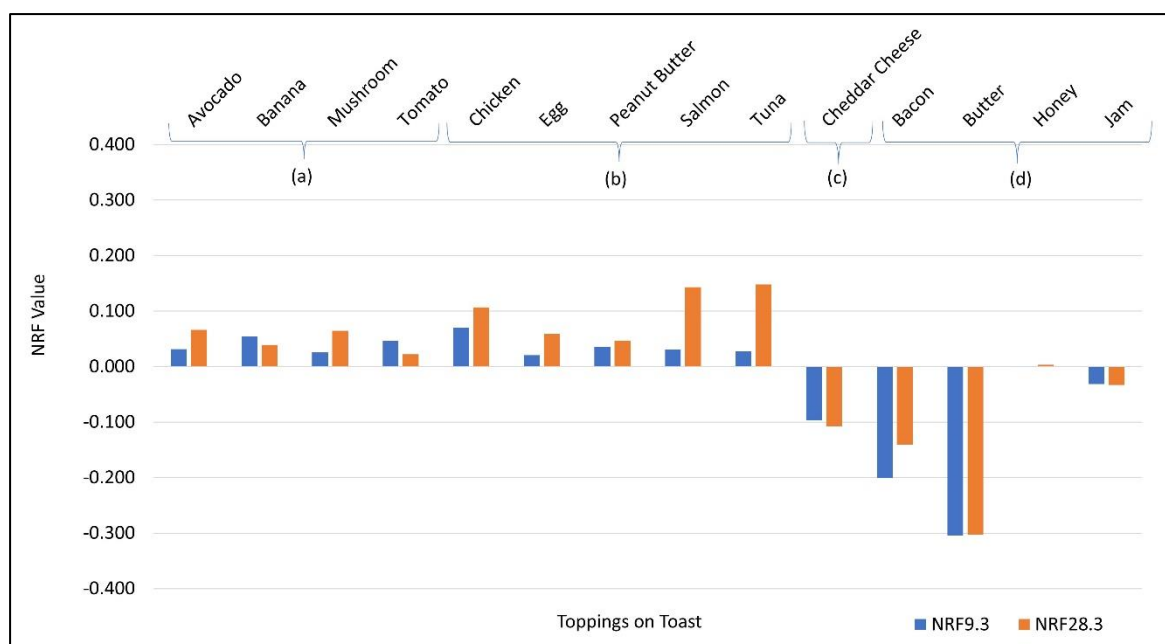


Figure 5.8 $NRF_{9.3}$ and $NRF_{28.3}$ values for all the 14 selected toast toppings representing the four food groups: (a) Vegetables and fruits; (b) Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; (c) Dairy milk and dairy milk products, mostly low and reduced fat; and (d) Discretionary foods.

This is explained by the relatively high LIM scores for butter, bacon, and cheese, compared to the other toppings. In the case of jam, the low NR_n value combined with the higher LIM value resulted in its negative NRF score. The $NRF_{28.3}$ values for most of the toppings were higher than their $NRF_{9.3}$ scores. Of these, the largest difference between the $NRF_{9.3}$ and $NRF_{28.3}$ indices was for salmon and tuna with the $NRF_{28.3}$ scores being ~ 5 times more than the $NRF_{9.3}$ value for both. This general trend of higher scores for the $NRF_{28.3}$ index was also seen in the NR_n comparisons in Figure 5.3 as mentioned earlier (where the NR_{28} scores were higher than the NR_9 scores for most of the toppings). As with the NR_n scores, the exceptions to this trend were banana, tomato, cheddar cheese, and jam.

5.3.1.3 nLCA scores

The nLCA results for the toppings are presented in Table 5.2. This table effectively represents the climate change impact scores alongside a separate midpoint nutrition impact category comprising the NRF scores.

Table 5.2 nLCA results presented per serve for the environmental (climate change impact) and nutritional values (NR₉, LIM, NRF, and Energy Density) for each of the 14 selected toast toppings, colour-coded by the quartile in which each score is categorized

	Vegetables and fruits				Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat					Dairy milk and dairy milk products, mostly low and reduced fat	Discretionary foods			
	Avocado	Banana	Mushroom	Tomato	Chicken	Egg	Peanut Butter	Salmon	Tuna	Cheddar Cheese	Bacon	Butter	Honey	Jam
GWP (kg CO ₂ eq./serve)	0.07	0.10	0.21	0.22	0.36	0.23	0.06	0.42	0.38	0.38	0.40	0.22	0.04	0.04
NR ₉	0.07	0.06	0.04	0.05	0.10	0.07	0.08	0.06	0.06	0.08	0.05	0.03	0.001	0.00
NR ₂₈	0.11	0.04	0.08	0.02	0.13	0.10	0.09	0.17	0.18	0.07	0.11	0.03	0.003	0.00
LIM	0.04	0.00	0.01	0.00	0.03	0.04	0.05	0.03	0.03	0.17	0.25	0.33	0.000	0.03
NRF _{9.3}	0.03	0.05	0.03	0.05	0.07	0.02	0.04	0.03	0.03	-0.10	-0.20	-0.30	0.001	-0.03
NRF _{28.3}	0.07	0.04	0.06	0.02	0.11	0.06	0.05	0.14	0.15	-0.11	-0.14	-0.30	0.003	-0.03
Energy Density (ED) (kcal)	185	105	58	12	155	134	189	84	96	168	232	147	61	47
Assigned ranking weights	Assigned colour for codes quartiles	GWP	NR ₉	NR ₂₈	LIM	NRF _{9.3}	NRF _{28.3}	ED						
4		≤ 0.07	≥ 0.07	≥ 0.11	≤ 0.01	≥ 0.04	≥ 0.07	≤ 61						
3		> 0.07 ≤ 0.22	≥ 0.06 < 0.07	≥ 0.08 < 0.11	> 0.01 ≤ 0.03	≥ 0.03 < 0.04	≥ 0.04 < 0.07	> 61 ≤ 120						
2		> 0.22 ≤ 0.38	≥ 0.04 < 0.06	≥ 0.03 < 0.08	> 0.03 ≤ 0.05	≥ -0.03 < 0.03	≥ -0.03 < 0.04	> 120 ≤ 168						
1		> 0.38	< 0.04	< 0.03	> 0.05	< -0.03	< -0.03	> 168						

For the ranking process, a weighting value from 1 (worst) to 4 (best) was assigned to each of the quartiles for climate change, and the NRF_{9.3} and NRF_{28.3} scores. Only the NRF values were used in this part of the analysis because they include both nutrients to limit and encourage. Two ranking sets were then calculated: set A is the average of the toppings' climate change and NRF_{9.3} quartile ranking weights, and set B is the average of the toppings' climate change and NRF_{28.3} quartile ranking weights (Table 5.3). Peanut butter and avocado ranked in the top two positions (best scores) in both ranking sets A and B. Cheddar cheese and bacon rank lowest and butter second to last (worst scores) in both ranking sets. Overall, the ranking of the toppings doesn't change significantly between the two ranking sets – in fact, all the toppings just move up or down one position between the ranking sets except tomato, which changes by two positions.

Table 5.3 Ranking sets A and B for toppings, based on assigned values for quartile-categorized scores for climate change, NRF_{9.3} and NRF_{28.3} (RA_{scores} and RB_{scores})

Ranking Score	Ranking Set A (based on RA _{scores})	Ranking Set B (based on RB _{scores})
4 (best)	Peanut Butter	Avocado
3.5	Avocado, Banana, Tomato	Peanut Butter
3	Chicken, Honey, Jam, Mushroom	Banana, Chicken, Honey, Jam, Mushroom, Tuna
2.5	Tuna	Egg, Salmon, Tomato
2	Butter, Egg, Salmon	Butter
1.5	-	-
1 (worst)	Bacon, Cheddar Cheese	Bacon, Cheddar Cheese

5.3.2 Comparison of results using other reference units

The nLCA results for the 14 toppings are presented for each of the three FUs in Table 5.4. When using different FUs, the climate change results for some toppings differ markedly. In particular, for tomato the climate change result is 8.5 times higher when using the 100 kcal rather than serve size as the reference unit.

Table 5.4 nLCA results for all 14 selected toast toppings, with respect to three reference units – mass, energy, and serve size (bl stands for baseline) colour-coded by the quartile in which each score is categorized

	Vegetables and Fruits				Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat					Dairy milk and dairy milk products, mostly low and reduced fat	Discretionary Foods			
	Avocado	Banana	Mushroom	Tomato	Chicken	Egg	Peanut Butter	Salmon	Tuna	Cheddar Cheese	Bacon	Butter	Honey	Jam
GWP (kg CO ₂ eq./serve)_bl	0.07	0.10	0.21	0.22	0.35	0.23	0.06	0.42	0.38	0.38	0.39	0.22	0.04	0.04
NRF _{9.3} _serve_bl	0.03	0.05	0.03	0.05	0.07	0.02	0.04	0.03	0.03	-0.10	-0.20	-0.30	0.00	-0.03
NRF _{28.3} _serve_bl	0.07	0.04	0.06	0.02	0.11	0.06	0.05	0.14	0.15	-0.11	-0.14	-0.30	0.00	-0.03
GWP (kg CO ₂ eq./100 g)	0.08	0.09	0.26	0.28	0.45	0.46	0.19	0.73	0.55	0.96	0.79	1.10	0.20	0.26
NRF _{9.3} _mass_100 g	0.04	0.05	0.03	0.06	0.09	0.04	0.12	0.05	0.04	-0.24	-0.37	-0.64	0.01	-0.20
NRF _{28.3} _mass_100 g	0.08	0.03	0.08	0.03	0.13	0.12	0.16	0.25	0.21	-0.27	-0.28	-0.63	0.02	-0.21
GWP (kg CO ₂ eq./100 kcal)	0.04	0.10	0.69	1.86	0.62	0.25	0.03	0.50	0.40	0.23	0.41	0.15	0.07	0.09
NRF _{9.3} _energy_100 kcal	0.02	0.05	0.04	0.39	0.06	0.02	0.02	0.04	0.03	-0.06	-0.10	-0.09	0.00	-0.07
NRF _{28.3} _energy_100 kcal	0.04	0.04	0.11	0.18	0.10	0.07	0.02	0.17	0.15	-0.06	-0.07	-0.09	0.01	-0.07
Assigned ranking weights	Assigned colour codes for quartiles	GWP/serve_bl	NRF _{9.3} _serve_bl	NRF _{28.3} _serve_bl	GWP/100 g	NRF _{9.3} _mass_100 g	NRF _{28.3} _mass_100 g	GWP/100 kcal	NRF _{9.3} _energy_100 kcal	NRF _{28.3} _energy_100 kcal				

4		≤ 0.07	≥ 0.04	≥ 0.07	≤ 0.2	≥ 0.05	≥ 0.13	≤ 0.09	≥ 0.04	≥ 0.11	
3		> 0.07 ≤ 0.22	≥ 0.03 < 0.04	≥ 0.04 < 0.07	> 0.2 ≤ 0.36	≥ 0.04 < 0.05	≥ 0.06 < 0.13	> 0.09 ≤ 0.25	≥ 0.02 < 0.04	≥ 0.04 < 0.11	<
2		> 0.22 ≤ 0.38	≥ -0.03 < 0.03	≥ -0.03 < 0.04	> 0.36 ≤ 0.73	≥ -0.2 < 0.04	≥ -0.21 < 0.06	> 0.25 ≤ 0.5	≥ -0.06 < 0.02	≥ -0.06 < 0.04	<
1		> 0.38	< -0.03	< -0.03	> 0.73	< -0.2	< -0.21	> 0.5	< -0.06	< -0.06	

The topping with the highest climate change result is different for each reference unit: salmon based on serve size, butter per 100 g, and tomato per 100 kcal. Overall, vegetables, fruits and protein-rich foods perform better nutritionally and environmentally across all three reference units, whereas cheese and toppings that are considered discretionary foods have the lowest scores.

In a subsequent step, the toppings were ranked using the combined climate change impact and nutritional scores as per Section 5.3.1.3. Two ranking sets (A and B) were assessed for the two additional FUs – mass (100 g) and energy (100 kcal). These ranking sets are presented in Table 5.5 along with the baseline ranking set (i.e. per serve size). Avocado, peanut butter and banana appear in the top two ranks for the three FUs in ranking set A. While tomato is ranked second per serve and per 100 g in ranking set A, it moves down two ranks with the 100 kcal FU. For ranking set B, avocado and peanut butter appear in the top two ranks for all three scenarios. Comparing across the two ranking sets, peanut butter and avocado are in the first two ranks, and butter, bacon, and cheddar cheese are in the last two ranks, across all three scenarios in both ranking sets. The change in the ranking position of food items between ranking set A and B is outlined in Appendix E, Table E6 for each topping across the three FUs. The toppings which change ranks between the two ranking sets for each FU, move up or down by only one place with two exceptions. The first exception is mushroom which moves down two places in Scenario B per 100 g, and the second is tomato which moves down two places in scenario B per serve size and per 100 g.

Table 5.5 Toppings ranked as per the two ranking scenarios*, across three FUs (serve, mass and energy)

Ranking Score	Ranking Scenario A (per serve)	Ranking Scenario A (per 100 g)	Ranking Scenario A (per 100 kcal)	Ranking Scenario B (per serve)	Ranking Scenario B (per 100 g)	Ranking Scenario B (per 100 kcal)
4 (best)	Peanut Butter	Banana, Peanut Butter	-	Avocado	Peanut Butter	-
3.5	Avocado, Banana, Tomato	Avocado, Tomato	Avocado, Banana, Peanut Butter	Peanut Butter	Avocado	Avocado
3	Chicken, Honey, Jam, Mushroom	Chicken, Honey, Salmon	Egg, Honey, Salmon	Banana, Chicken, Honey, Jam, Mushroom, Tuna	Banana, Chicken, Honey, Mushroom, Salmon, Tuna	Egg, Banana, Honey, Peanut Butter, Salmon, Tuna
2.5	Tuna	Jam, Tuna, Egg, Mushroom	Cheddar Cheese, Chicken, Mushroom, Jam, Tomato, Tuna	Egg, Salmon, Tomato	Egg, Jam, Tomato	Cheddar Cheese, Jam, Mushroom, Tomato
2	Butter, Egg, Salmon	-	Butter	Butter	-	Bacon, Butter, Chicken
1.5	-	Cheddar Cheese	Bacon	-	-	-
1 (worst)	Bacon, Cheddar Cheese	Bacon, Butter	-	Bacon, Cheddar Cheese	Bacon, Butter, Cheddar Cheese	-

* Ranking Scenario A - average of climate change impact and NRF_{9.3} assigned values; Ranking Scenario B – average of climate change impact and NRF_{28.3} assigned values

5.4 Discussion and conclusion

5.4.1 Methodological choices

5.4.1.1 *Nutrients to consider in indices*

The baseline results show that the inclusion of different numbers of nutrients in a scoring system changes the nLCA results for food items in a meal context (Table 5.2). However, this is not sufficient to change the ranking of the toppings more than one place in the two ranking systems used in this study (Table 5.3). Tomato is an exception – it changes from second to fourth place in the ranking using $NR_{9.3}$ and $NR_{28.3}$ index respectively. This occurs because the NR_n score for tomato is significantly lower (>50%) for 28 compared to 9 nutrients to encourage. This is due to the presence of Vitamin C in tomato in significant proportions in both indices and relatively smaller contributions by the additional nutrients in the NR_{28} index. Interestingly, the difference between the NR_9 and NR_{28} indices for jam was very similar to that for tomato – its NR_{28} score was 49% lower than its NR_9 score, however, its ranking did not change between the ranking sets. This could be a result of its significantly lower climate change impact score (82%), and higher LIM score (34%) relative to tomato. Thus, this study shows that, as some foods contain certain nutrients (included in the NR_9 index) in more significant proportions than others (for example, calcium in cheese, dietary fibre in the plant-based toppings, and protein in most of the animal-based ones), these nutrients contribute significantly to the NR_9 score of these toppings. However, using an expanded index can ‘dilute’ the total score because of the additional nutrients (not included in NR_9) in the expanded index which only make very small contributions to the total score.

The nutrient contribution analyses (Figures 5.5-5.7) offer some interesting insights. Unlike the NR_9 index, where the proteins and fat-soluble vitamins contribute more to the total score than water-soluble vitamins, the latter usually dominate the NR_{28} index relative to the proteins and fat-soluble vitamins. Thus, water-soluble vitamins gain significance (from the perspective of proportional contribution to the total nutritional value) when an expanded index is used. This

has implications for diets deficient in micronutrients, especially in Low- and Middle-Income Countries (LMICs). In particular, ‘priority micronutrients’⁴⁵ include two water-soluble vitamins (folate and vitamin B12) (Beal & Ortenzi, 2022), neither of which are included in the NR₉ index. Thus, it is recommended to include these in nLCA studies when a more nuanced approach is needed to study a population whose diet is lacking in these essential micronutrients (Katz-Rosene et al., 2023).

Secondly, most toppings in this case study contain unsaturated fats and these contributed markedly to the NR₂₈ values of several toppings. A number of national and international nutritional guidelines encourage dietary substitution of trans and saturated fats with foods containing MUFAs and PUFAs (especially omega 3 and 6) (Ministry of Health, 2020; National Health and Medical Research Council, 2013a; World Health Organization (WHO), 2023) due to their reported positive impacts on human health (Mozaffarian et al., 2010; Ravaut et al., 2021). Green et al. (2020) also notes that not accounting for healthy fats penalizes foods that are rich in them. Although the rankings did not change significantly in this study when including additional nutrients in the NRF_{28.3} index, the presence of MUFAs and PUFAs was instrumental in moving some of the toppings up a rank, e.g. avocados, tuna and eggs. Therefore, if food composition data on MUFAs and PUFAs is available, it might be useful to include them in studies focused on comparing/ranking foods within meals or meals themselves.

Overall, the results of this study align with the views of other authors who note that limiting the number of nutrients in nutritional profiling algorithms can be sufficient to obtain a representative understanding of the nutritional value of food items or diets (as mentioned in Section 5.1). The rankings obtained in this study did not change much between indices; for example, the top two best and worst performing foods were the same in both. However, with

⁴⁵ These include six micronutrients which diets in LMICs are most frequently deficient in – iron, zinc, folate, vitamin B12, vitamin A, and calcium.

specific food items that are significantly richer in certain nutrients not included in indices with fewer nutrients to encourage, it could be useful to expand the index to include them, as this does affect the final rankings to some extent. For example, avocados (rich in MUFAs) ranked second when using the NRF_{9.3} index but moved up a rank to become the best performing topping with NRF_{28.3}. It is also important to note that these findings are specific to this study and could change if other toppings were considered (because the rankings are relative within the studied toppings). Thus, overall, the choice of nutrients considered for the index will also depend on the diversity of the food items/meals being studied – a more diverse range of foods could benefit from an expanded index, to allow for a better representation of the nutritional (and consequently nLCA) value of those foods.

5.4.1.2 Choice of functional/reference unit

While choice of FU influences the nLCA values, it does not appear to alter the topping rankings significantly (Tables 5.4 and 5.5).

Food-related LCA studies usually use mass-based FUs; however, when assessing food choices within a meal context, it is preferable to use serve size rather than equal mass-based units as it reflects more realistic consumption and hence nutrient intakes at the meal or diet level (Grigoriadis et al., 2021; Jolliet, 2022; Masset et al., 2014). The only challenge is that, unlike foods within the same food group that are likely to have similar serve sizes as they are commonly standardized by the amount of dietary energy provided in a serve (see, for example, Hallström et al. (2019) who studied seafood), serve sizes are generally not standardized across different food items from different food groups within meals⁴⁶. Moreover, while standardized serve sizes can be useful for comparative studies like the current study, the actual amounts/portions consumed may vary substantially between people and for different

⁴⁶ An exception to this is the U.S. Reference Amount Customarily Consumed (RACC) – a metric developed and mandated by the U.S. Food and Drug Administration (FDA) to roughly standardize actual serve sizes for a food product (Berardy et al., 2019; Drewnowski, 2017; Grigoriadis et al., 2021).

consumption situations (for instance, a small snack versus a meal or component of a dish). One solution to variable serve- and portion sizes is using an energy-based metric energy either on a 100 kcal basis or standardized to the recommended daily energy intake (usually ~2000 kcal). Energy-based FUs account for variable water quantities or calorific densities of different food items and therefore can make it possible to calculate nutritional value of food independent of portion or serve size (Drewnowski, 2005; Fern et al., 2015; Schaubroeck et al., 2018). Although some argue in favor of using such energy-based metrics (see for example, Green et al., 2023), serve size is still the most representative of actual amounts consumed in one sitting, and therefore more pertinent to the meal context. In fact, Bianchi et al. (2020) suggest that if standardized serve sizes are developed in future, that are also aligned with international standards, then it should be considered a ‘preferred choice’ for FU selection in nLCA studies.

5.4.1.3 Weighting and capping

Most nLCA studies exclude a specific weighting process i.e. they weight all the nutrients equally due to a lack of scientific consensus on the appropriate criteria to use for this purpose (Drewnowski, 2017; Green et al., 2020). Some authors recommend weighting of nutrients in an index using the distance-to-target approach i.e. dividing the DRI by the average intake of that nutrient (Bianchi et al., 2020; Hallström et al., 2019; Ridoutt, 2021; Strid et al., 2021). Some data is available in the New Zealand Nutrition Survey of 2011 (University of Otago & Ministry of Health, 2011) for the Estimated Prevalence of Inadequate Intake (EPII) of certain nutrients in New Zealand adults and could potentially be used to develop a scarcity-weighted index. However, using >10-year-old data would probably not be adequately representative of the current situation. Moreover, the survey contains EPII data for only twelve nutrients and excludes, for example, Vitamin D, folate, and iodine. However, if more up-to-date data were available, this would be an interesting extension to the analysis.

Capping refers to restricting the ‘good’ nutrients to 100% of their RDI to avoid over-counting their benefits if there are large amounts in the studied food items. Capping has been applied in

several nLCA studies (e.g. Arsenault et al., 2012; Batlle-Bayer et al., 2020; Doran-Browne et al., 2015; Drewnowski et al., 2015; Green et al., 2021; Hallström et al., 2019; Van Kernebeek et al., 2014), but there is currently no consensus on its use (Kyttä et al., 2023; McLaren et al., 2021). Some researchers suggest that, within the diet (i.e. at the food item or meal-level), nutrients should be left uncapped (Hallström et al., 2018; Mazac et al., 2023), because generally diets comprise a diverse range of foods and if a food has lower levels of a particular nutrient, this is compensated by other foods with higher quantities of that nutrient. Green et al. (2023) recommends that nutrients should be capped in a total diet-level study because it represents a complete set of nutrients and therefore, these should not exceed RDIs. Green et al. (2023) also suggest that consuming a particular nutrient in excess of its recommended value not only provides no additional benefits but can even be harmful to health. However, while this may be true for some nutrients, other nutrients may actually have beneficial health impacts when present in concentrations higher than the RDI. For example, certain vitamins, minerals like selenium, PUFAs like omega 3, and dietary fibre have been noted to lower the risk of chronic health issues like heart disease, cancer, and degenerative cognitive issues like Alzheimer's when consumed at levels above the RDI (National Medical Health and Research Council, 2017). As the current study was focused on a single meal and none of the nutrients in the studied food items exceeded their RDIs per serve, this was not a relevant consideration.

5.4.1.4 Other choices

Other methodological choices made in this study that affected the ranking of the different meals include:

- Quantile-based ranking: Toppings were categorized into quartiles based on their nutritional and climate change impact scores. Other studies have used quintiles (e.g. Bianchi et al., 2020; Green et al., 2023; Strid et al., 2021). The choice of such quantiles will depend upon the number of alternatives considered and the range of the results. One challenge with quantile-based ranking is that the results may have to be re-calculated if toppings are

excluded or added. However, this is only required if their values are very different from the range of values in the rest of the sample.

- **Weighting of climate change impacts and nutritional value:** These two aspects were weighted equally. However, weighting in LCA implies value judgements and equal weighting may not be representative of how much importance consumers place on nutritional versus climate change impacts. One way to address this is to offer the consumer the option to use their own value judgements. For example, on a website or app employing this method, a tab could be included where the consumer could input their own preference-based weights, and the final scores would be calculated accordingly. This weighting process could potentially also be extended to additional environmental impacts if more environmental impact categories were included in the analysis.

Bioavailability of nutrients: Nutrient bioavailability refers to the ‘fraction of an ingested nutrient that becomes available for use and storage in the body’ (Melse-Boonstra, 2020). Bioavailability is an important aspect of nutritional studies because it explains how the consumption of a nutrient translates into actual health effects. Protein bioavailability has been studied with respect to its quality, i.e. the digestibility of the different amino acids (using for example, the DIAAS score) within plant- and animal-based proteins (Adhikari et al., 2022; Bailey and Stein, 2019), linking protein quality and food sustainability (Moughan, 2021) and incorporating protein quality in nLCA studies (Berardy et al., 2019; McAuliffe et al., 2022; Sonesson et al., 2017). Animal-sourced foods are generally found to contain protein and some essential micronutrients in more bioavailable forms than plant-based foods (Beal et al., 2023). For example, iron is present in food as heme and non-heme iron; however, heme iron is only found in animal-based foods and is more bioavailable than non-heme iron (Skolmowska et al., 2019). Similarly, zinc and calcium are generally less bioavailable from plant-based compared to animal-derived foods due to the presence of antinutrients like phytates and oxalates in plants (although the concentrations of these will vary with each food) (Maares & Haase, 2020; Melse-Boonstra, 2020; Shkembi & Huppertz,

2022; Yusuf, 2023). Thus, bioavailability of nutrients is an important consideration for future studies as micronutrient inadequacy (and consequent deficiency) continues to be of major global concern, especially in vulnerable population groups such as women of reproductive age (Beal, 2024) or people in developing countries (Zhang et al., 2016). Further, 'food matrix' and 'meal effects' can also influence nutrient bioavailability and associated nutritional/health impacts (McLaren et al., 2021). Ideally, this would be integrated into the scoring system; however, given the lack of available data on this aspect, it remains a topic requiring further research.

- Choice of environmental impacts: As mentioned in Section 5.2.2, climate change was selected as the environmental impact indicator for this current study. However, this is an obvious limitation, particularly as food systems are associated with a wide range of environmental impacts. Future research should include other impact categories of particular significance to food systems, such as biodiversity loss, soil quality, land use change, and water use and pollution.

5.4.1.5 Data choices

For any single food item, the environmental impacts may be quite variable. This variability may be due to production practices, different varieties of the same product, seasonality and variable harvest times, packaging type and size, method of storage and length of storage before consumption, distance transported from farm/industry/packhouse gate to the end consumer, and end-of-life management practices. For example, with respect to production practices, tomatoes may be grown in heated greenhouses, passive or unheated greenhouses, or in the open field; eggs can be obtained from chickens in different housing conditions (caged, barn, free range); jam can be made from fresh fruit or from a semi-finished product using any one of three processes – freezing, drying, or via aseptic treatment; honey can be manufactured using stationary or migratory beehives; and salmon can be farmed in land-based/sea-based aquaculture systems or be wild caught (Appendix E, Table E7). The impact scores for these production methods can be markedly different for a food item e.g. tomatoes grown in an actively

heated greenhouse can have a climate change impact score of up to 2.5 kg CO₂ eq./kg compared to 0.3 kg CO₂ eq./kg when grown outside in the open field. Similarly, farmed salmon generally has been reported to have higher impacts (2.2-6.4 kg CO₂ eq./kg salmon) than wild caught salmon (0.8-1.2 kg CO₂ eq./kg salmon).

Production practices can also result in nutritional variability in the same type of food item – for example, farmed salmon contains more PUFAs than wild-caught ones (Colombo and Mazal, 2020). Crop farming systems can also have a significant impact on the nutritional quality of the food. For example, crops grown organically can have different nutrient compositions from conventionally grown crops (Mditshwa et al. 2017). Similarly, Montgomery et al. (2022) showed that crops grown via the regenerative method had increased levels of micronutrients and phytochemicals. The study also found that pork from animals in a regenerative farm had an improved fatty acid profile, including higher levels of omega-3 fatty acids. In addition to production practices, several other factors can impact the nutritional profile of crops, including genotype, climate, soil properties (such as soil pH and organic matter content), geographical factors like elevation, external predatory and disease stressors, as well as post-harvest handling, processing, and storage methods (Hornick, 1992).

In addition to production practices, different varieties of the same product can also have variable environmental impacts. For example, canned pink salmon (one of the toast toppings in this study) is commonly consumed in New Zealand, but New Zealand also produces Chinook or King salmon, which is consumed (less commonly) as fresh, hot or cold smoked fillets. The climate change impact of New Zealand King Salmon was recently calculated at 8.2 kg CO₂ eq./kg edible flesh (thinkstep-anz, 2023); this value is 30% higher than the canned pink salmon value used in this study. This could be at least partly due to the production practice-related variability mentioned earlier – New Zealand King salmon is farmed, whereas the latter is most likely wild caught. For button mushrooms, this study used a climate change impact of 2 kg CO₂ eq./kg mushroom at shed gate. Tongpool and Pongpat (2013) calculated a similar value for shiitake

mushrooms, but Ueawiwatsakul et al. (2014) calculated a value of 4 kg CO₂ eq./kg sajor-caju mushrooms at shed gate.

Nutritional content of a food can also vary with seasonality. For example, avocados can remain unharvested longer than other fruits as they ripen only after harvest (Wang et al., 2012). In New Zealand, avocados are often 'left on the tree' to be harvested as per market requirements from September through April. As the fruit's water content decreases, the dry matter increases as the season progresses, leading to increased concentrations for most of the nutrients (see Appendix E, Table E8) and changing the nutritional value per serve size.

5.4.2 Future directions and conclusion

The current study looked at food items within a single meal context and demonstrated that overall rankings don't change significantly when an expanded index is used in place of a limited one. This finding should be tested by undertaking additional case studies on more diverse samples of simple and/or composite meals.

Regarding application areas, in addition to helping consumers make more informed food choices, the nLCA-based method in this study could also be used to help restaurateurs or catering services to identify nutrition-poor and high environmental impact meals in their menus and change them accordingly to offer more nutritionally and environmentally sustainable options. With respect to home cooked meals, there are several existing websites and apps to help consumers make healthier food choices as per nutritional recommendations (e.g. Harvard University, 2023; U.S. Department of Agriculture, 2023) as well as those offering a wide range of recipes to help consumers plan and cook meals at home (e.g. All Recipes, 2023). The nLCA method developed in this study could be used to rank meals on existing or new websites and apps, as well as food composition databases and even national food-based dietary guidelines.

Meals can either be home cooked or obtained outside the home from restaurants/café's, institutional canteens, catered services, or ready meals. In the case of cooked food obtained away from home, or even home delivered meal kits, information about the food items with

respect to the variables mentioned in Section 5.4.1.5 would, in most cases, be available to the service providers (for example, a restaurant would know whether it is sourcing free-range or factory farmed eggs, button or shiitake mushrooms, early or late season avocados, etc.). However, in the case of home-cooked meals based on recipes provided in apps or on websites, it is left to the consumer to source the meal components/ingredients. In this case, the variability mentioned in Section 5.4.1.5 can be communicated to the consumer by providing nutritional and environmental score ranges. To this end, it might be useful to investigate the extent of the influence of the abovementioned variables on nLCA-based meal rankings in future studies. This could help streamline the factors which have the largest impacts on individual food items, those which affect majority of the food items, and finally those which influence the nLCA-based meal-level rankings.

With respect to other avenues for future research, weighting the nutrients in a food or meal according to their relative importance (for example, by the average intake of specific nutrients in the target population's diet) is meaningful if directly relevant to the population of interest and should be considered, especially in studies with a focus on specific population groups based on geographical location, age, gender, reproductive status, or socioeconomic variables (Bianchi et al., 2022). For example, regional weighting factors based on nutritional deficiencies/scarcity were applied to nutrient indices in studies conducted in Peru (Avadí and Fréon, 2015), Australia (Ridoutt, 2021) and Sweden (Hallström et al., 2019). Future research might also consider how such nLCA-based meal rankings change when considering the cost of food and affordability, as they have a direct bearing on consumer purchasing decisions (Headey and Alderman, 2019; Hirvonen et al., 2020).

Overall, this study showed that using an expanded nutritional index does not necessarily result in higher NRF scores and also does not alter the final rankings of the toppings in a ToT meal significantly. However, some of the toppings which have high proportions of nutrients not included in the NRF_{9.3} index move up a rank in the baseline scenario (e.g. avocados that are high in MUFAs, and eggs, which contain a large amount of PUFAs, MUFAs, and selenium). Thus, while

the NRF_{9,3} index can generally identify the best, medium, and worst performing foods in this meal context, an expanded index could produce more nuanced rankings. More case studies are needed to understand how an expanded index would influence a larger and more diverse range of meals or foods within a meal context. In addition, investigations into the variability of different factors related to assessment of foods and meals (e.g. bioavailability of nutrients, target population nutrient deficiencies, agricultural production practices, seasonality, etc.) can offer more resolution to this nLCA ranking method, which can then be developed further for integration into new or existing tools for improved consumer decision-making. Moreover, although this study takes a primarily consumption-oriented perspective to sustainable nutrition, increased consumer demand for low impact, nutrient-rich meals could also drive systemic change in farming/production practices in the long-term.

References

- Aceves-Martins, M., Bates, R. L., Craig, L. C. A., Chalmers, N., Horgan, G., Boskamp, B., and de Roos, B. (2022). Food-level analysis to identify dietary choices with the highest nutritional quality and lowest greenhouse gas emissions and price. *Frontiers in Nutrition*, 9. <https://doi.org/10.3389/fnut.2022.851826>
- Adhikari, S., Schop, M., de Boer, I. J. M., and Huppertz, T. (2022). Protein quality in perspective: a review of protein quality metrics and their applications. *Nutrients*, 14(5), 947. <https://doi.org/10.3390/nu14050947>
- All Recipes. (2023). *Allrecipes-About Us*. <https://www.allrecipes.com/about-us-6648102> (Accessed 13 October 2023)
- Arsenault, J. E., Fulgoni, V. L., Hersey, J. C., and Muth, M. K. (2012). A novel approach to selecting and weighting nutrients for nutrient profiling of foods and diets. *Journal of the Academy of Nutrition and Dietetics*, 112(12), 1968–1975. <https://doi.org/10.1016/j.jand.2012.08.032>
- Avadí, A., and Fréon, P. (2015). A set of sustainability performance indicators for seafood: Direct human consumption products from Peruvian anchoveta fisheries and freshwater aquaculture. *Ecological Indicators*, 48, 518–532. <https://doi.org/10.1016/j.ecolind.2014.09.006>
- Bailey, H. M., and Stein, H. H. (2019). Can the digestible indispensable amino acid score methodology decrease protein malnutrition. *Animal Frontiers: The Review Magazine of Animal Agriculture*, 9(4), 18–23. <https://doi.org/10.1093/af/vfz038>
- Batlle-Bayer, L., Bala, A., Roca, M., Lemaire, E., Aldaco, R., and Fullana-i-Palmer, P. (2020). Nutritional and environmental co-benefits of shifting to “Planetary Health” Spanish tapas. *Journal of Cleaner Production*, 271, 1–9. <https://doi.org/10.1016/j.jclepro.2020.122561>
- Beal, T., and Ortenzi, F. (2022). Priority micronutrient density in foods. *Frontiers in Nutrition*, 9. <https://doi.org/10.3389/fnut.2022.806566>
- Beal, T., Gardner, C. D., Herrero, M., Iannotti, L. L., Merbold, L., Nordhagen, S., and Mottet, A. (2023). Friend or Foe? The Role of Animal-Source Foods in Healthy and Environmentally Sustainable Diets. *The Journal of Nutrition*, 153, 409–425. <https://doi.org/10.1016/j.tjnut.2022.10.016>
- Beal, T. (2024). Environmentally protective diets may come with trade-offs for micronutrient adequacy. *The American Journal of Clinical Nutrition*, 119(4), 872–873. <https://doi-org.ezproxy.massey.ac.nz/10.1016/j.ajcnut.2024.01.028>

- Berardy, A., Johnston, C. S., Plukis, A., Vizcaino, M., and Wharton, C. (2019). Integrating protein quality and quantity with environmental impacts in life cycle assessment. *Sustainability*, 11(10), Article 10. <https://doi.org/10.3390/su11102747>
- Bianchi, M., Hallström, E., Parker, R. W. R., Mifflin, K., Tyedmers, P., and Ziegler, F. (2022). Assessing seafood nutritional diversity together with climate impacts informs more comprehensive dietary advice. *Communications Earth and Environment*, 3(1), Article 1. <https://doi.org/10.1038/s43247-022-00516-4>
- Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U., and Hallström, E. (2020). Systematic evaluation of nutrition indicators for use within food LCA studies. *Sustainability*, 12(21), Article 21. <https://doi.org/10.3390/su12218992>
- Calderón, L. A., Herrero, M., Laca, A., and Díaz, M. (2018). Environmental impact of a traditional cooked dish at four different manufacturing scales: From ready meal industry and catering company to traditional restaurant and homemade. *The International Journal of Life Cycle Assessment*, 23(4), 811–823. <https://doi.org/10.1007/s11367-017-1326-7>
- Chapa, J., Farkas, B., Bailey, R. L., and Huang, J.Y. (2020). Evaluation of environmental performance of dietary patterns in the United States considering food nutrition and satiety. *Science of The Total Environment*, 722, 137672. <https://doi.org/10.1016/j.scitotenv.2020.137672>
- Clark, M. A., Springmann, M., Hill, J., and Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences*, 116(46), 23357–23362. <https://doi.org/10.1073/pnas.1906908116>
- Clark, M., Hill, J., and Tilman, D. (2018). The diet, health, and environment trilemma. *Annual Review of Environment and Resources*, 43(1), 109–134. <https://doi.org/10.1146/annurev-environ-102017-025957>
- Clark, M., Springmann, M., Rayner, M., Scarborough, P., Hill, J., Tilman, D., Macdiarmid, J.I., Fanzo, J., Bandy, L. and Harrington, R.A. (2022). Estimating the environmental impacts of 57,000 food products. *Proceedings of the National Academy of Sciences*, 119(33), e2120584119. <https://doi.org/10.1073/pnas.2120584119>
- Coelho, C. R. V., Pernollet, F., and van der Werf, H. M. G. (2016). Environmental Life Cycle Assessment of diets with improved omega-3 fatty acid profiles. *PLOS ONE*, 11(8), e0160397. <https://doi.org/10.1371/journal.pone.0160397>

- Colombo, S. M., and Mazal, X. (2020). Investigation of the nutritional composition of different types of salmon available to Canadian consumers. *Journal of Agriculture and Food Research*, 2, 100056. <https://doi.org/10.1016/j.jafr.2020.100056>
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), Article 3. <https://doi.org/10.1038/s43016-021-00225-9>
- Davis, J., Sonesson, U., Baumgartner, D. U., and Nemecek, T. (2010). Environmental impact of four meals with different protein sources: Case studies in Spain and Sweden. *Food Research International*, 43(7), 1874–1884. <https://doi.org/10.1016/j.foodres.2009.08.017>
- De Smalen, A. W., Chan, Z. X., Abreu Lopes, C., Vanore, M., Loganathan, T., and Pocock, N. S. (2021). Developing an evidence assessment framework and appraising the academic literature on migrant health in Malaysia: A scoping review. *BMJ Open*, 11(1), e041379. <https://doi.org/10.1136/bmjopen-2020-041379>
- Doran-Browne, N. A., Eckard, R. J., Behrendt, R., and Kingwell, R. S. (2015). Nutrient density as a metric for comparing greenhouse gas emissions from food production. *Climatic Change*, 129(1–2), 73–87. <https://doi.org/10.1007/s10584-014-1316-8>
- Drew, J., Cleghorn, C., Macmillan, A., and Mizdrak, A. (2020). Healthy and climate-friendly eating patterns in the New Zealand context. *Environmental Health Perspectives*, 128(1), 017007. <https://doi.org/10.1289/EHP5996>
- Drewnowski, A. (2005). Concept of a nutritious food: Toward a nutrient density score. *The American Journal of Clinical Nutrition*, 82(4), 721–732. <https://doi.org/10.1093/ajcn/82.4.721>
- Drewnowski, A. (2009). Defining nutrient density: development and validation of the Nutrient Rich Foods index. *Journal of the American College of Nutrition*, 28(4), 421S–426S. <https://doi.org/10.1080/07315724.2009.10718106>
- Drewnowski, A. (2017). Uses of nutrient profiling to address public health needs: From regulation to reformulation. *Proceedings of the Nutrition Society*, 76(3), 220–229. <https://doi.org/10.1017/S0029665117000416>
- Drewnowski, A., Amanquah, D., and Gavin-Smith, B. (2021). Perspective: how to develop nutrient profiling models intended for global use: a manual. *Advances in Nutrition*, 12(3), 609–620. <https://doi.org/10.1093/advances/nmab018>

- Drewnowski, A., Dwyer, J., King, J. C., and Weaver, C. M. (2019). A proposed nutrient density score that includes food groups and nutrients to better align with dietary guidance. *Nutrition Reviews*, 77(6), 404–416. <https://doi.org/10.1093/nutrit/nuz002>
- Drewnowski, A., Maillot, M., and Darmon, N. (2009). Should nutrient profiles be based on 100 g, 100 kcal or serve size? *European Journal of Clinical Nutrition*, 63(7), 898–904. <https://doi.org/10.1038/ejcn.2008.53>
- Drewnowski, A., Rehm, C. D., Martin, A., Verger, E. O., Voinnesson, M., and Imbert, P. (2015). Energy and nutrient density of foods in relation to their carbon footprint. *The American Journal of Clinical Nutrition*, 101(1), 184–191. <https://doi.org/10.3945/ajcn.114.092486>
- Dudley, N., and Alexander, S. (2017). Agriculture and biodiversity: A review. *Biodiversity*, 18(2–3), 45–49. <https://doi.org/10.1080/14888386.2017.1351892>
- Dutton, M. T., Lopez, I. A., Brown, C. P., and Simmons, J. V. (2015). Interdisciplinary synergy in the teaching of applied community-based research methods. *Pedagogy in Health Promotion*, 1(3), 158–163. <https://doi.org/10.1177/2373379915580583>
- Eme, P. E., Douwes, J., Kim, N., Foliaki, S., and Burlingame, B. (2019). Review of methodologies for assessing sustainable diets and potential for development of harmonised indicators. *International Journal of Environmental Research and Public Health*, 16(7), 1184. <https://doi.org/10.3390/ijerph16071184>
- Erickson, J. and Slavin, J. (2015). Total, added, and free sugars: Are restrictive guidelines science-based or achievable? *Nutrients* 7(4), 2866–2878.
- Ernstoff, A., Tu, Q., Faist, M., Del Duce, A., Mandlebaum, S., and Dettling, J. (2019). comparing the environmental impacts of meatless and meat-containing meals in the United States. *Sustainability*, 11(22), Article 22. <https://doi.org/10.3390/su11226235>
- Esteve-Llorens, X., Darriba, C., Moreira, M. T., Feijoo, G., and González-García, S. (2019). Towards an environmentally sustainable and healthy Atlantic dietary pattern: Life cycle carbon footprint and nutritional quality. *Science of The Total Environment*, 646, 704–715. <https://doi.org/10.1016/j.scitotenv.2018.07.264>
- Falandysz, J. (2008). Selenium in edible mushrooms. *Journal of Environmental Science and Health. Part C, Environmental Carcinogenesis and Ecotoxicology Reviews*, 26(3), 256–299. <https://doi.org/10.1080/10590500802350086>

- Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A., and Drewnowski, A. (2015). The nutrient balance concept: a new quality metric for composite meals and diets. *PLOS ONE*, 10(7), e0130491. <https://doi.org/10.1371/journal.pone.0130491>
- Fernández-Ríos, A., Laso, J., Campos, C., Ruiz-Salmón, I., Hoehn, D., Cristóbal, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P., Puig, R., Aldaco, R., and Margallo, M. (2021). Towards a Water-Energy-Food (WEF) nexus index: A review of nutrient profile models as a fundamental pillar of food and nutrition security. *Science of The Total Environment*, 789, 147936. <https://doi.org/10.1016/j.scitotenv.2021.147936>
- Food and Agriculture Organization of the United Nations (FAO). (2020). *The State of Food and Agriculture 2020: Overcoming water challenges in agriculture*. FAO. Available for download at: <https://doi.org/10.4060/cb1447en>
- Food and Agriculture Organization of the United Nations (FAO). (2010). *Greenhouse gas emissions from the dairy sector: A Life Cycle Assessment*. Available for download at: <https://openknowledge.fao.org/home>
- Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). (2019). *Sustainable healthy diets—Guiding principles*. Available for download at: <https://www.who.int/publications/i/item/9789241516648>
- Food Standards Australia New Zealand (FSANZ). (2021). *Australia New Zealand Food Standards Code – Standard 1.2.8, Nutrition information requirements*. <https://www.foodstandards.gov.au/food-standards-code> (Accessed 5 September 2023)
- Fulgoni, V. L., III, Keast, D. R., and Drewnowski, A. (2009). Development and validation of the Nutrient-Rich Foods index: a tool to measure nutritional quality of foods. *The Journal of Nutrition*, 139(8), 1549–1554. <https://doi.org/10.3945/jn.108.101360>
- García-Herrero, L., De Menna, F., and Vittuari, M. (2019). Food waste at school. The environmental and cost impact of a canteen meal. *Waste Management*, 100, 249–258. <https://doi.org/10.1016/j.wasman.2019.09.027>
- Global Nutrition Report. (2021). *2021 Global Nutrition Report: The state of global nutrition*. Available for download at: <https://globalnutritionreport.org/reports/2021-global-nutrition-report/>
- Global Panel on Agriculture and Food Systems for Nutrition. (2020). *Foresight 2.0. Future food systems: For people, planet, and prosperity*. Available for download at: <https://foresight.glopan.org/>

- González-García, S., Esteve-Llorens, X., Moreira, M. T., and Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *Science of The Total Environment*, 644, 77–94. <https://doi.org/10.1016/j.scitotenv.2018.06.339>
- Graham, F., Russell, J., Holdsworth, M., Menon, M., and Barker, M. (2019). Exploring the Relationship between Environmental Impact and Nutrient Content of Sandwiches and Beverages Available in Cafés in a UK University. *Sustainability*, 11(11), Article 11. <https://doi.org/10.3390/su11113190>
- Green, A., Nemecek, T., Chaudhary, A., and Mathys, A. (2020). Assessing nutritional, health, and environmental sustainability dimensions of agri-food production. *Global Food Security*, 26, 100406. <https://doi.org/10.1016/j.gfs.2020.100406>
- Green, A., Nemecek, T., and Mathys, A. (2023). A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: The metrics and their assumptions matter. *The International Journal of Life Cycle Assessment*, 28, 1326–1347. <https://doi.org/10.1007/s11367-023-02210-9>
- Green, A., Nemecek, T., Smetana, S., and Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696. <https://doi.org/10.1016/j.jclepro.2021.127696>
- Grigoriadis, V., Nugent, A., and Brereton, P. (2021). Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends in Food Science and Technology*, 112, 298–311. <https://doi.org/10.1016/j.tifs.2021.03.047>
- Gu, D., Andreev, K., and Dupre, M. E. (2021). Major trends in population growth around the world. *China CDC Weekly*, 3(28), 604–613. <https://doi.org/10.46234/ccdcw2021.160>
- Guan, V. X., Neale, E. P., and Probst, Y. C. (2022). Consumption of avocado and associations with nutrient, food and anthropometric measures in a representative survey of Australians: A secondary analysis of the 2011–2012 National Nutrition and Physical Activity Survey. *British Journal of Nutrition*, 128(5), 932–939. <https://doi.org/10.1017/S0007114521003913>
- Guo, A., Bryngelsson, S., Strid, A., Bianchi, M., Winkvist, A., and Hallström, E. (2022). Choice of health metrics for combined health and environmental assessment of foods and diets: A systematic review of methods. *Journal of Cleaner Production*, 365, 132622. <https://doi.org/10.1016/j.jclepro.2022.132622>

- Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., and Ziegler, F. (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production*, 230, 402–411. <https://doi.org/10.1016/j.jclepro.2019.04.229>
- Hallström, E., Carlsson-Kanyama, A., and Börjesson, P. (2015). Environmental impact of dietary change: A systematic review. *Journal of Cleaner Production*, 91, 1–11. <https://doi.org/10.1016/j.jclepro.2014.12.008>
- Hallström, E., Davis, J., Woodhouse, A., and Sonesson, U. (2018). Using dietary quality scores to assess sustainability of food products and human diets: A systematic review. *Ecological Indicators*, 93, 219–230. <https://doi.org/10.1016/j.ecolind.2018.04.071>
- Harrison, M. R., Palma, G., Buendia, T., Bueno-Tarodo, M., Quell, D., and Hachem, F. (2022). A Scoping Review of Indicators for Sustainable Healthy Diets. *Frontiers in Sustainable Food Systems*, 5. <https://www.frontiersin.org/articles/10.3389/fsufs.2021.822263>
- Harvard University. (2023). *The nutrition source - Healthy eating plate*. <https://www.hsph.harvard.edu/nutritionsource/healthy-eating-plate/> (Accessed 1 November 2023).
- Headey, D. D., and Alderman, H. H. (2019). The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. *The Journal of Nutrition*, 149(11), 2020–2033. <https://doi.org/10.1093/jn/nxz158>
- Heller, M. C., Keoleian, G. A., and Willett, W. C. (2013). Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review. *Environmental Science and Technology*, 47(22), 12632–12647. <https://doi.org/10.1021/es4025113>
- Henriksson, P. JG., Cucurachi, S., Guinée, J. B., Heijungs, R., Troell, M., and Ziegler, F. (2021). A rapid review of meta-analyses and systematic reviews of environmental footprints of food commodities and diets. *Global Food Security*, 28, 100508. <https://doi.org/10.1016/j.gfs.2021.100508>
- Hirvonen, K., Bai, Y., Headey, D., and Masters, W. A. (2020). Affordability of the EAT–Lancet reference diet: A global analysis. *The Lancet Global Health*, 8(1), e59–e66. [https://doi.org/10.1016/S2214-109X\(19\)30447-4](https://doi.org/10.1016/S2214-109X(19)30447-4)
- Hoolohan, C., Berners-Lee, M., McKinsty-West, J., and Hewitt, C. N. (2013). Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices. *Energy Policy*, 63, 1065–1074. <https://doi.org/10.1016/j.enpol.2013.09.046>

- Hornick, S. (1992). Factors affecting the nutritional quality of crops. *American Journal of Alternative Agriculture*, 7(1/2), 63-68.
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. Available for download at: <https://www.ipbes.net/global-assessment>
<https://doi.org/10.5281/zenodo.3831673>
- Jolliet, O. (2022). Integrating Dietary Impacts in Food Life Cycle Assessment. *Frontiers in Nutrition*, 9, 1-7. <https://doi.org/10.3389/fnut.2022.898180>
- Jones, A. D., Hoey, L., Blesh, J., Miller, L., Green, A., and Shapiro, L. F. (2016). A Systematic review of the measurement of sustainable diets. *Advances in Nutrition*, 7(4), 641–664.
<https://doi.org/10.3945/an.115.011015>
- Kägi, T., Zschokke, M., and Dinkel, F. (2012). *Nutrient based functional unit for meals*. In 8th International Conference on LCA in the Agri-Food Sector, Rennes, France.
<https://doi.org/10.13140/RG.2.1.1689.7367>
- Katz-Rosene, R., Ortenzi, F., McAuliffe, G. A., and Beal, T. (2023). Levelling foods for priority micronutrient value can provide more meaningful environmental footprint comparisons. *Communications Earth and Environment*, 4(1), 287. <https://doi.org/10.1038/s43247-023-00945-9>
- Kyttä, V., Kårlund, A., Pellinen, T., Pietiläinen, O., Tuomisto, H. L., Kolehmainen, M., Pajari, A.-M., and Saarinen, M. (2023). Product-group-specific nutrient index as a nutritional functional unit for the Life Cycle Assessment of protein-rich foods. *The International Journal of Life Cycle Assessment*, 28, 1672-1688. <https://doi.org/10.1007/s11367-023-02217-2>
- Lukas, M., Rohn, H., Lettenmeier, M., Liedtke, C., and Wiesen, K. (2016). The nutritional footprint – integrated methodology using environmental and health indicators to indicate potential for absolute reduction of natural resource use in the field of food and nutrition. *Journal of Cleaner Production*, 132, 161–170. <https://doi.org/10.1016/j.jclepro.2015.02.070>
- Maares, M., and Haase, H. (2020). A Guide to Human Zinc Absorption: General Overview and Recent Advances of In Vitro Intestinal Models. *Nutrients*, 12(3), 762.
<https://doi.org/10.3390/nu12030762>

- Martínez-Blanco, J., Antón, A., Rieradevall, J., Castellari, M., and Muñoz, P. (2011). Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization. *The International Journal of Life Cycle Assessment*, 16(1), 12–26. <https://doi.org/10.1007/s11367-010-0238-6>
- Masset, G., Soler, L.G., Vieux, F., Darmon, N. (2014). Identifying sustainable foods: the relationship between environmental impact, nutritional quality, and prices of foods representative of the French diet. *Journal of the Academy of Nutrition and Dietetics*, 114(6), 862-869.
- Masset, G., Vieux, F., and Darmon, N. (2015). Which functional unit to identify sustainable foods? *Public Health Nutrition*, 18(13), 2488–2497. <https://doi.org/10.1017/S1368980015000579>
- Mazac, R., Järviö, N., and Tuomisto, H. L. (2023). Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. *Science of The Total Environment*, 876, 162796. <https://doi.org/10.1016/j.scitotenv.2023.162796>
- McAuliffe, G. A., Takahashi, T., Beal, T., Huppertz, T., Leroy, F., Buttriss, J. et al. (2022). Protein quality as a complementary functional unit in life cycle assessment (LCA). *The International Journal of Life Cycle Assessment*, 28, 146-158. <https://doi.org/10.1007/s11367-022-02123-z>
- McAuliffe, G. A., Takahashi, T., and Lee, M. R. F. (2018). Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. *Food and Energy Security*, 7(3), e00143. <https://doi.org/10.1002/fes3.143>
- McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O. et al. (2021). *Integration of environment and nutrition in life cycle assessment of food Items: Opportunities and challenges*. <https://doi.org/10.4060/cb8054en>
- Meier, T., and Christen, O. (2013). Environmental impacts of dietary recommendations and dietary styles: Germany as an example. *Environmental Science and Technology*, 47(2), 877–888. <https://doi.org/10.1021/es302152v>
- Mekonnen, M. M., and Hoekstra, A.Y. (2014). Water footprint benchmarks for crop production: A first global assessment. *Ecological Indicators*, 46, 214–223. <https://doi.org/10.1016/j.ecolind.2014.06.013>
- Melse-Boonstra, A. (2020). Bioavailability of micronutrients from nutrient-dense whole foods: zooming in on dairy, vegetables, and fruits. *Frontiers in Nutrition*, 7, 101. <https://doi.org/10.3389/fnut.2020.00101>

- Mditshwa, A., Magwaza, L.S., Tesfay, S.Z., and Mbili, N. (2017). Postharvest quality and composition of organically and conventionally produced fruits: A review. *Scientia Horticulturae*, 216, 148-159.
- Ministry of Health. (2020). *Eating and activity guidelines for New Zealand adults—2020*. Available for download at: <https://www.tewhatauora.govt.nz/health-services-and-programmes/nutrition/eating-and-activity-guidelines>
- Montgomery, D.R., Biklé, A., Archuleta, R., Brown, P., and Jordan, J. (2022). Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. *PeerJ* 10, e12848 <https://doi.org/10.7717/peerj.12848>
- Moughan, P. J. (2021). Population protein intakes and food sustainability indices: The metrics matter. *Global Food Security*, 29, 100548. <https://doi.org/10.1016/j.gfs.2021.100548>
- Mozaffarian, D., Micha, R., and Wallace, S. (2010). Effects on coronary heart disease of increasing polyunsaturated fat in place of saturated fat: a systematic review and meta-analysis of randomized controlled trials. *PLOS Medicine*, 7(3), e1000252. <https://doi.org/10.1371/journal.pmed.1000252>
- National Health and Medical Research Council. (2013a). *Educator guide - Information for nutrition educators*. https://www.eatforhealth.gov.au/sites/default/files/files/the_guidelines/n55b_eat_for_health_educators_guide.pdf
- National Health and Medical Research Council. (2013b). *Eat for health. Australian dietary guidelines. Providing the scientific evidence for healthier Australian diets*. Available for download at: <https://www.eatforhealth.gov.au/guidelines/guidelines>
- National Heart Lung and Blood Institute. (2023). *Serve sizes and portions*. <https://www.nhlbi.nih.gov/health/educational/wecan/eat-right/distortion.htm> (Accessed 7 October 2023)
- National Medical Health and Research Council. (2017). *Nutrient Reference Values (NRVs) for Australia and New Zealand including Recommended Dietary Intakes*. Available for download at: <https://www.nhmrc.gov.au/about-us/publications/nutrient-reference-values-australia-and-new-zealand-including-recommended-dietary-intakes>
- New Zealand Food Composition Database (NZFCD). (2022). *New Zealand Food Composition Database online search*. <https://www.foodcomposition.co.nz/search> (Accessed 8 October 2023)

- Notarnicola, B., Tassielli, G., Renzulli, P.A., and Giudice, A.L. (2015). "Life Cycle Assessment in the agri-food sector: an overview of its key aspects, international initiatives, certification, labelling schemes and methodological issues," in *Life Cycle Assessment in the Agri-food Sector*, eds. B. Notarnicola, R. Salomone, L. Petti, P.A. Renzulli, R. Roma, and A.K. Cerutti (Switzerland: Springer International Publishing), 1-57.
- Notarnicola, B., Sala, S., Anton, A., McLaren, S. J., Saouter, E., and Sonesson, U. (2017). The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, 140, 399–409.
<https://doi.org/10.1016/j.jclepro.2016.06.071>
- O'Neill, A. (2023). *Age structure in New Zealand 2022*.
<https://www.statista.com/statistics/436395/age-structure-in-new-zealand/> (Accessed 13 September 2023)
- Oonincx, D., and de Boer, I. (2012). Environmental impact of the production of mealworms as a protein source for humans—A life cycle assessment. *PLOS ONE*, 7(12), e51145–e51145.
<https://doi.org/10.1371/journal.pone.0051145>
- Ravaut, G., Légiot, A., Bergeron, K.-F., and Mounier, C. (2021). Monounsaturated fatty acids in obesity-related inflammation. *International Journal of Molecular Sciences*, 22(1), Article 1.
<https://doi.org/10.3390/ijms22010330>
- Ridoutt, B. (2021). An alternative Nutrient Rich Food Index (NRF-ai) Incorporating prevalence of inadequate and excessive nutrient intake. *Foods*, 10(12), Article 12.
<https://doi.org/10.3390/foods10123156>
- Rozin, P., and Siegal, M. (2003). Vegemite as a marker of national identity. *Gastronomica*, 3(4), 63-67. <https://doi.org/10.1525/gfc.2003.3.4.63>
- Saarinen, M., Fogelholm, M., Tahvonen, R., and Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, 149, 828–844. <https://doi.org/10.1016/j.jclepro.2017.02.062>
- Saarinen, M., Kurppa, S., Virtanen, Y., Usva, K., Mäkelä, J., and Nissinen, A. (2012). Life Cycle Assessment approach to the impact of home-made, ready-to-eat and school lunches on climate and eutrophication. *Journal of Cleaner Production*, 28, 177–186.
<https://doi.org/10.1016/j.jclepro.2011.11.038>
- Sabaté, J. (2019). *Connecting health and nutrition*. In *Environmental Nutrition* (p. xv). Elsevier.
<https://doi.org/10.1016/B978-0-12-811660-9.09987-2>

- Sala, S., Anton, A., McLaren, S. J., Notarnicola, B., Saouter, E., and Sonesson, U. (2017). In quest of reducing the environmental impacts of food production and consumption. *Journal of Cleaner Production*, 140, 387–398. <https://doi.org/10.1016/j.jclepro.2016.09.054>
- Salazar T, M. B., Cai, H., Bailey, R., and Huang, J.-Y. (2019). Defining nutritionally and environmentally healthy dietary choices of omega-3 fatty acids. *Journal of Cleaner Production*, 228, 1025–1033. <https://doi.org/10.1016/j.jclepro.2019.04.359>
- Sameshima, H., Akamatsu, R., Hayashi, F., and Takemi, Y. (2023). Estimation of greenhouse gas emissions from Japanese healthy meals with different protein sources. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1232198>
- Scarborough, P., Arambepola, C., Kaur, A., Bhatnagar, P., and Rayner, M. (2010). Should nutrient profile models be ‘category specific’ or ‘across-the-board’? A comparison of the two systems using diets of British adults. *European Journal of Clinical Nutrition*, 64(6), 553–560. <https://doi.org/10.1038/ejcn.2010.31>
- Schaubroeck, T., Ceuppens, S., Luong, A. D., Benetto, E., De Meester, S., Lachat, C., and Uyttendaele, M. (2018). A pragmatic framework to score and inform about the environmental sustainability and nutritional profile of canteen meals, a case study on a university canteen. *Journal of Cleaner Production*, 187, 672–686. <https://doi.org/10.1016/j.jclepro.2018.03.265>
- Shkembi, B., and Huppertz, T. (2022). Calcium absorption from food products: food matrix effects. *Nutrients*, 14(1), Article 1. <https://doi.org/10.3390/nu14010180>
- Skolmowska, D., and Głąbska, D. (2019). Analysis of heme and non-heme iron intake and iron dietary sources in adolescent menstruating females in a national Polish sample. *Nutrients*, 11(5), 1049. <https://doi.org/10.3390/nu11051049>
- Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., and Witthöft, C. (2017). Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. *Journal of Cleaner Production*, 140, 470–478. <https://doi.org/10.1016/j.jclepro.2016.06.115>
- Spanos, S., Kenda, A. S., and Vartanian, L. R. (2015). Can serving-size labels reduce the portion-size effect? A pilot study. *Eating Behaviors*, 16, 40–42. <https://doi.org/10.1016/j.eatbeh.2014.10.007>
- Springmann, M., Clark, M., Mason-D’Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L. et al. (2018a). Options for keeping the food system within environmental limits. *Nature*, 562(7728), Article 7728. <https://doi.org/10.1038/s41586-018-0594-0>

- Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M., and Scarborough, P. (2018b). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level detail. *The Lancet Planetary Health*, 2(10), e451–e461. [https://doi.org/10.1016/S2542-5196\(18\)30206-7](https://doi.org/10.1016/S2542-5196(18)30206-7)
- Stats NZ. (2023). *National Population Estimates: at 30 June 2023*. <https://www.stats.govt.nz/information-releases/national-population-estimates-at-30-june-2023/> (Accessed 13 September 2023)
- Strid, A., Hallström, E., Sonesson, U., Sjons, J., Winkvist, A., and Bianchi, M. (2021). Sustainability Indicators for Foods Benefiting Climate and Health. *Sustainability*, 13(7), Article 7. <https://doi.org/10.3390/su13073621>
- Sturtewagen, L., De Soete, W., Dewulf, J., Lachat, C., Lauryssen, S., Heirman, B., Rossi, F., and Schaubroeck, T. (2016). Resource use profile and nutritional value assessment of a typical Belgian meal, catered or home cooked, with pork or Quorn™ as protein source. *Journal of Cleaner Production*, 112, 196–204. <https://doi.org/10.1016/j.jclepro.2015.09.006>
- Takacs, B., Stegemann, J. A., Kalea, A. Z., and Borrion, A. (2022). Comparison of environmental impacts of individual meals—Does it really make a difference to choose plant-based meals instead of meat-based ones? *Journal of Cleaner Production*, 379, 134782. <https://doi.org/10.1016/j.jclepro.2022.134782>
- The Academy of Nutrition and Dietetics. (2023). *Serve size vs portion size: is there a difference?* <https://www.eatright.org/health/wellness/nutrition-panels-and-food-labels/serving-size-vs-portion-size-is-there-a-difference> (Accessed 4 October 2023)
- thinkstep-anz. (2023). *LCA of assessment of New Zealand-farmed King salmon*. Available for download at: <https://www.thinkstep-anz.com/resrc/case-studies/lca-nz-farmed-king-salmon/>
- Tongpool, R., and Pongpat, P. (2013). Analysis of shiitake environmental performance via Life Cycle Assessment. *International Journal of Environmental Science and Development*, 4(5), 552-557.
- Ueawiwatsakul, S., Mungcharoen, T. and Tongpool, R. (2014). Life Cycle Assessment of Sajor-caju Mushroom (*Pleurotus Sajor-caju*) from different sizes of farms in Thailand. *International Journal of Environmental Science and Development*, 5(5), 435-439.

- United Nations Framework Convention on Climate Change (UNFCCC). (2023b). *Embracing sustainable agriculture: leaders unite in the UAE declaration, prioritizing resilient food systems and climate action*. <https://www.cop28.com/en/food-and-agriculture> (Accessed 1 December 2023)
- United Nations Framework Convention on Climate Change (UNFCCC). (2023a). *Climate action and COP28 - What is the global stock take?* <https://unfccc.int/> (Accessed 2 December 2023)
- University of Otago, & Ministry of Health. (2011). *A focus on nutrition: Key findings of the 2008/09 New Zealand Adult Nutrition Survey*. Available for download at: <https://www.health.govt.nz/publications/a-focus-on-nutrition-key-findings-from-the-200809-nz-adult-nutrition-survey>
- U.S. Department of Agriculture. (2023). *My plate*. <https://www.myplate.gov/> (Accessed 4 December 2023)
- Van Kernebeek, H. R. J., Oosting, S. J., Feskens, E. J. M., Gerber, P. J., and De Boer, I. J. M. (2014). The effect of nutritional quality on comparing environmental impacts of human diets. *Journal of Cleaner Production*, 73, 88–99. <https://doi.org/10.1016/j.jclepro.2013.11.028>
- Verdinelli, S., and Scagnoli, N. I. (2013). Data display in qualitative research. *International journal of qualitative methods*, 12(1), 359–381. <https://doi.org/10.1177/160940691301200117>
- Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. I. (2012). Climate change and food systems. *Annual Review of Environment and Resources*, 37(1), 195–222. <https://doi.org/10.1146/annurev-environ-020411-130608>
- Vieux, F., Soler, L. G., Touazi, D., and Darmon, N. (2013). High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults. *The American Journal of Clinical Nutrition*, 97(3), 569–583. <https://doi.org/10.3945/ajcn.112.035105>
- Virtanen, Y., Kurppa, S., Saarinen, M., Katajajuuri, J.-M., Usva, K., Mäenpää, I., Mäkelä, J., Grönroos, J., and Nissinen, A. (2011). Carbon footprint of food – approaches from national input–output statistics and a LCA of a food portion. *Journal of Cleaner Production*, 19(16), 1849–1856. <https://doi.org/10.1016/j.jclepro.2011.07.001>
- Vriesekoop, F., Russell, C., Tziboula-Clarke, A., Jan, C., Bois, M., Farley, S., and McNamara, A. (2022). The iconisation of yeast spreads—love them or hate them. *Beverages*, 8(1), Article 1. <https://doi.org/10.3390/beverages8010016>

- Wang, M., Zheng, Y., Khuong, T., and Lovatt, C. J. (2012). Effect of harvest date on the nutritional quality and antioxidant capacity in 'Hass' avocado during storage. *Food Chemistry*, 135(2), 694–698. <https://doi.org/10.1016/j.foodchem.2012.05.022>
- Weidema, B. P., and Stylianou, K. S. (2020). Nutrition in the Life Cycle Assessment of foods—Function or impact? *The International Journal of Life Cycle Assessment*, 25(7), 1210–1216. <https://doi.org/10.1007/s11367-019-01658-y>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. et al. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- World Health Organization (WHO). (2015). *Guideline: sugars intake for adults and children*. World Health Organization. Available for download at: <https://www.who.int/publications/i/item/9789241549028>
- World Health Organization (WHO). (2023). *Total fat intake for the prevention of unhealthy weight gain in adults and children: WHO guideline*. World Health Organisation. Available for download at: <https://www.who.int/publications/i/item/9789240073654>
- Yusuf, E. H. (2023). Comparison of Life Cycle Assessments and Nutritional Contents of Soy Protein and Wheat Protein (Seitan) Based Vegan Bacon Products for Human and Environmental Health. *Journal of the Science of Food and Agriculture*, 103(7), 3315–3321. <https://doi.org/10.1002/jsfa.12507>
- Zhang, Z., Goldsmith, P. D., and Winter-Nelsen, A. (2016). The importance of animal source foods for nutrient sufficiency in the developing world: the Zambia scenario. *Food and Nutrition Bulletin*, 37(3), 303–316. <https://doi.org/10.1177/0379572116647823>

Chapter 6 Discussion and conclusion

6.1 Research aim, questions, and objectives

Agri-food production systems are associated with a range of environmental impacts including climate change, water scarcity, aquatic and terrestrial ecotoxicity, marine and freshwater eutrophication, biodiversity loss, and land use impacts (Crippa et al., 2021; FAO, 2021; Ferreira et al., 2022; Mekonnen & Hoekstra, 2014; Poore & Nemecek, 2018). At the same time, from a consumption perspective, they are linked with health-related challenges like malnutrition (nutritional deficiencies and overweight/obesity) and non-communicable diseases (NCDs) (Clark et al., 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020). Thus, a move to sustainable agri-food production systems *and* healthy diets is vital to the transition to Sustainable Food Systems (SFS), especially given the growing population and the concomitant increase in agri-food demands expected in coming decades (European Union, 2020; FAO & WHO, 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020; United Nations, 2023; Willett et al., 2019).

A sustainable consumption and production (SCP) approach to SFS takes a holistic view of agri-food systems along the whole life cycle of foods (Sonnemann et al., 2018; UNEP, 2017), and LCA is widely used in SCP to assess the environmental impacts of agri-food systems (Clark et al., 2022; McLaren et al., 2021a; Notarnicola et al., 2017). Agri-food voluntary sustainability systems (VSS) have emerged as an important multi-stakeholder approach to enable cleaner food production, while indirectly supporting more sustainable food consumption as well (Tayleur et al., 2018; UNFSS et al., 2020). However, the role of LCA in development of indicators for agri-food VSS in the context of SCP has not been widely researched (Chapter 1, Section 1.4.4) – and there has only recently been research interest in the integration of nutritional aspects with LCA to inform SCP from a consumer perspective (Berardy et al., 2019; Kyttä et al., 2023; McLaren et al., 2021a) (Chapter 5, Section 5.1). This research therefore investigated how LCA could be used to facilitate more sustainable agri-food systems from a production perspective (in the context of

developing indicators for VSS), and also to support consumers to make more environmentally and nutritionally informed food consumption decisions from a consumption perspective.

These aspects are relevant to the New Zealand context because: 1) the average New Zealand diet includes ultra-processed and discretionary foods rich in added sugar, salt and red meat, and this (along with sedentary lifestyles) has contributed to a rise in obesity, NCDs and related mortality (Mackay et al., 2022; Starck et al., 2021); 2) the climate and land use impacts of conventional agriculture, as well as its polluting effects on New Zealand's freshwater systems, are increasingly a topic of concern (MfE, 2023; Palliser et al., 2019); 3) New Zealand is stagnating or making slow progress on several agriculture, nutrition, and environment-related SDGs (SDG 2, 12, 13, 14, 15) (Sachs et al., 2025); and 4) credible evidence is needed to underpin New Zealand's reputation as a 'clean, green country' in order to support its export-oriented primary sectors (MPI, 2023) .

The overall research aim therefore was '**to identify how LCA-based approaches can support more sustainable agri-food production and consumption in New Zealand.**' The role of VSS was chosen as a particular focus for agri-food production systems due to the dearth of LCA-based indicators in agri-food VSS as well as sparse research on the same (Chapter 1). And the role of nutritional LCA (nLCA) was chosen as a particular focus for food consumption due the need to provide consumers with combined life cycle-based nutritional and environmental information to consumers. nLCA has emerged as a promising approach for this, however it is still a nascent area of research, with methodological development in progress, especially at the meal level (Chapter 5).

Two RQs were developed:

- RQ1 – What is the role of LCA in the development of performance-based indicators for VSS criteria for a New Zealand agri-food sector?
- RQ2 – What is the role of nLCA in helping New Zealand consumers make informed consumption decisions based on the combined nutritional value and environmental impacts of food?

This chapter discusses the insights obtained from the research in the context of RQ1 (Section 6.2) and RQ2 (Section 6.3). Section 6.4 outlines the implications of this research for government policy and for industry in New Zealand. Limitations and recommendations for future research are noted in Section 6.5, and Section 6.6 concludes the thesis.

6.2 Role of LCA in developing performance-based indicators for agri-food sector VSS in New Zealand

This section provides a summary of implications for indicator development for a sector-wide VSS for New Zealand avocados, based on the research (Section 6.2.1). The rationale for these implications as well as their potential applicability to wider New Zealand agri-food sectors is discussed in Section 6.2.2.

6.2.1 Implications for performance-based indicators for agri-food VSS

A qualitative study on the perceptions of stakeholders in the New Zealand avocado sector highlighted that the sector was well-placed as a case study for the development of LCA-based performance metrics and indicators for use in a sector-wide VSS. On this basis, a comprehensive LCA study was conducted on the New Zealand avocado sector (Chapters 3 and 4). The main aim of the study was to determine the environmental hotspots in the New Zealand avocado life cycle, including how variability in the supply chains influenced the results, and to evaluate how the results of the study could be used to develop indicators and benchmarks for a sector-wide VSS. Environmental impacts were assessed for five impact categories: climate change, eutrophication, water use, and freshwater and terrestrial ecotoxicity. In the first part of the study, impacts were modelled for the commercially productive orchard stage, and the early and late orchard stages as well. National and regional benchmarks were calculated, and LCA-based indicator development was discussed – in particular, how to account for orchard variability, the orchard life cycle, and key methodological aspects (Chapter 3, Section 3.5). In the second part of the study, the system boundaries were extended to include downstream stages to the first point of sale in domestic and international markets. Results were discussed in terms of the

environmental hotspots along the life cycle, differences in supply chains, and how to develop indicators and benchmarks for these post-harvest stages (Chapter 4, Section 4.5).

The main findings from this research and their implications for the development of life-cycle based indicators for use in a VSS for the New Zealand avocado sector are summarised in Table 6.1. It should be noted that the implications are based on several important assumptions:

- The impact categories considered in the avocado LCA study were climate change, eutrophication, water use, freshwater ecotoxicity, and terrestrial ecotoxicity. These categories were considered to be most relevant in an earlier materiality assessment conducted by NZ Avocado (Chapter 3, Section 3.2.2). The implications might change if other impact categories were included in the analysis.
- The inferences are oriented towards development of indicators for VSS focused on stakeholders in the avocado supply chain with influence over specific activities extending from the orchard through to the point of arrival at the first point of sale (RDC in domestic markets and port of landing for export destinations).
- The scope of decisions to be influenced by the VSS is the short- and medium-term rather than longer-term strategic decisions for the New Zealand avocado sector. The VSS indicators should be developed to influence decisions under the control of affected stakeholders i.e. orchardists for an orchard-oriented VSS, and packers and distributors/exporters for the wider New Zealand avocado sector. Longer-term strategic decisions by the sector should also be informed by LCA studies but are outside the scope of this research.

Table 6.1 Main findings of LCA study and associated implications for indicator development

<i>Life cycle stage</i>	<i>Insight topic</i>	<i>Insight and implication</i>	<i>Thesis chapters and sections</i>
Full life cycle	1. Environmental hotspots in avocado supply chain	Insight: Orchard stage is the most important hotspot for most supply chains. However, the post-harvest stages make notable contributions to total supply chain impacts (41% and 22% to overseas port and domestic RDC respectively). Also, including post-overseas port stages when exporting avocados to Australia increases impacts and these stages contributed notably to total impacts. Implication: Indicators should not focus only on the orchard but extend to packing and distribution stages as well. While post-port stages have notable contribution to the life cycle impacts, including them in indicator development may not be suitable as these stages lie beyond the influence of New Zealand stakeholders.	Chapter 4, Sections 4.5.1.1 and 4.5.1.5
	2. Assessment of water use	Insight: Unspecified national level AWARE characterisation factors for water use impacts are much higher and less representative than the regionally variable sub-national, non-agricultural factors for New Zealand. Implication: Water use impacts are highly site-specific. Therefore, when characterised water use impacts are assessed for indicator development, the exact sources of water should be identified, and the respective sub-national factors should be used to inform the decision-making.	Chapter 3, Section 3.5.2.4; Chapter 4, Section 4.5.2.2
Orchard stage	3. Specific activities contributing to environmental impacts	Insight: For the orchard stage, fertiliser and fuel were the hotspots for all categories except water scarcity, where direct water use was the main contributing factor. Agrichemical production and transport also had equally notable contributions to orchard-stage ecotoxicity impacts. Implication: Fertiliser and fuel use should be prioritised for overall indicator development, and agrichemical use for ecotoxicity impacts, and direct on-orchard water application for water use impacts	Chapter 3, Section 3.5
	4. Variability amongst avocado orchards	Insight: High variability between orchards for both inputs and impacts was noted, within and between regions. Implication: National level results should not be used as benchmarks within the VSS as they do not account for the inter-regional variability among growers. Instead, regional scores are more appropriate as benchmarks. To address the variability between growers within a region as well, it would be more useful to	Chapter 3, Section 3.4.1 and 3.4.3

		have flexible, tiered benchmarks like those used by Cossu et al. (2023) for each region, instead of a pass/fail threshold.	
	5. Agricultural soil ecotoxicity not assessed	Insight: Current LCA methods do not allow for impacts on agricultural soil to be assessed as there is no consensus on whether agricultural soil is part of the technosphere or ecosphere. Implication: An additional indicator should be developed to measure the ecotoxicity impact of agrichemical inputs on orchard soil.	Chapter 3, Section 3.5.2.4
	6. Different characteristics of early (and late) years of orchard life cycle	Insight: When the whole orchard life was considered, the low and non-productive stages (i.e. establishment and end-of-life of orchard) had notable contributions to the avocado growing impact scores across impact categories. Implication: Separate indicators should be developed for the low and non-productive orchard stages. An area-based FU should be used to calculate these values.	Chapter 3, Section 3.5.2.3
	7. Water use assessment	Insight: Water use impacts are highly sensitive to the spatial disaggregation of water sources as mentioned above in point 2. At the orchard stage specifically, indirect water use has more significant water use impacts than direct water use on orchard when sub-regional characterisation factors are used. However, when using national factors, the on-orchard water use becomes the more significant contributing stage to water use impacts. Implication: Geographically-specific characterisation factors should be used for activities instead of the national-level factor. An alternative, in the absence of data on geographical locations, is to use volumetric water use as an indicator as this can be a suitable water use indicator that is meaningful to orchardists for enabling change.	Chapter 3, Section 3.5.2.4
Post-harvest stage	8. Priorities for distribution indicators	Insight: Markets for New Zealand avocado are unlikely to be influenced in the shorter term by environmental priorities, and so efficient transportation modes should be the priority focus for indicators. Also, at the post-harvest stages, mode of transport is more important than distance travelled. Implication: For the post-harvest stages, indicators should be based on a per t.km functional unit (rather than per kg of fruit). Additionally, a simple performance metric could be included as an airfreighting indicator, e.g. quantity of fruit transported by air per year for airfreighting fruit.	Chapter 4, Section 4.5.1.2
	9. Distinction between domestic	Insight: There is a significant difference between packaging used for exports versus domestic distribution; export packaging has much higher impacts.	Chapter 4, Section 4.5.1.3

	and export packaging	Implication: Two distinct packaging-related indicators should be used: one for export-aligned SLTs, and the other representing domestic distribution. For the latter, a weighted average of PC and BLF values (weighted by actual quantities used for each type of packaging) can be used as the benchmark.	
Post-harvest stage (minor inputs)	10. Business travel	Insight: Business travel associated with the packhouse and coolstore contributes <2% to the overall life cycle impacts. Implication: Business travel related to packhouse and coolstore activities can be excluded from indicator development	Chapter 4, Section 4.5.1.4
	11. Reuse of plastic crates (PCs)s for packaging	Insight: Including PC manufacture, use and end-of-life stages contributes less than 0.5% the overall LCA results, assuming at least a 50-time reuse of the PCs. Implication: If PCs are used at least 50 times, they can be classified as capital equipment and excluded from the LCA study. For the packaging indicators, they can be regarded as “free” inputs.	Chapter 4, Section 4.5.2.1

6.2.2 Rationale for implications

6.2.2.1 Hotspot identification (Table 6.1; point 1, point 3)

The avocado LCA study identified environmental hotspots that can inform indicator development for a sector-specific VSS (Table 6.1). An important insight was that, while the orchard stage was the hotspot for nearly all supply chain scenarios, the post-harvest stages also made notable contributions to the impacts (41% and 22% of total supply chain impacts up to the destination port for exports, and RDC for domestic supply respectively) (Chapter 4, Section 4.4.1). Therefore, the post-harvest stages should be included in a VSS for the avocado sector, contrary to the current focus on the growing stage of most existing VSS.

With respect to inputs/outputs and activities at the orchard, the following environmental hotspots were identified (Chapter 3, Section 3.5):

- Fuel use and fertiliser use were found to be the environmental hotspots at the orchard level for all impact categories except water use impacts.
- Specifically, for ecotoxicity impacts, agrichemical production (particularly copper-based fungicides) were equally significant contributors to orchard-stage impacts.

Thus, at the orchard stage, fuel and fertiliser use on the orchard be prioritised for overall indicator development. For ecotoxicity and water use impacts specifically, copper-based fungicide manufacture and transport, and direct water use on orchard should be prioritised respectively.

For the post-harvest stages (Chapter 4, Section 4.4), it was found that:

- The truck transport associated with domestic distribution to the South Island had larger impacts than shipping to Australia (albeit without modelling the onward distribution to retailers).
- For the different export destinations, airfreighting always had higher post-harvest impacts than shipping across all impact categories. Thus, airfreighting as a mode of transport is a major environmental hotspot in the New Zealand avocado sector for export markets.

- At the packhouse stage, SLT use was associated with much larger impacts than BLFs or PCs used for domestic packaging.

This has three specific implications. Firstly, distribution indicators for transport by sea, ship or rail should include an indicator based on impacts per t.km, as avocado supply chain stakeholders are likely to have more opportunity to influence this aspect as opposed to changing export destinations which is a highly strategic decision. Secondly, although airfreighting is not a frequently used mode of transport, its impacts are significant – therefore, a simple performance metric representing airfreight impacts is suggested, e.g. quantity of fruit airfreighted per year . Thirdly, there should be separate packaging indicators and associated benchmarks for export and domestic distribution supply chains.

In the wider agri-food context in New Zealand, supply chain dynamics differ between sectors, as do inputs/outputs and activities, and so the relative contribution of life cycle stages to overall impacts also vary. For the avocado sector, it was found that, while post-harvest stages had notable contributions to the overall life cycle impacts, the orchard stage remained the hotspot for most of the supply chain scenarios (Chapter 4, Section 4.5.1.1). These findings are distinct from other sectors' supply chains. For example, distribution to international destinations is the climate change hotspot for New Zealand apple and kiwifruit, and glass bottle manufacturing contributes the most to overall life cycle impacts in wine supply chains (McLaren et al., 2021b). These differences are seen in non-horticultural product sectors as well. For example, in New Zealand milk and beef/sheep meat export supply chains, the production stage accounts for the majority of the climate change impact in the life cycle (77-84% for milk exported to China; up to 95% for meat exported to USA, UK, Japan, and China) (Ledgard et al., 2021; Mazzetto et al., 2021). Distribution-related impacts are relatively low in these supply chains, because the products are usually sea-freighted, and the main contributor to the climate change impact is animal enteric methane. In contrast, seafood is not associated with methane emissions but often has to be airfreighted due to its short shelf life; in this case, the distribution stage contributes

more than the production stage for these supply chains (see, for example, thinkstep ANZ, 2021, 2023).

Differences in the relative significance of inputs/outputs and activities within life cycle stages should also be considered during hotspot analysis for indicator development. For example, electricity use in the coolstore is relatively much less for avocados compared to kiwifruit or apples. This is because avocados are climacteric fruit and need to be shipped as soon as possible after being harvested. Kiwifruit and apples, on the other hand, may stay in cool storage for months before they are shipped to their export destinations (Boschiero et al., 2019; McLaren et al., 2021b; Mithraratne et al., 2010). Similarly, feed production (and transport) for some animal-based sectors like poultry and seafood is known to be the most significant contributor to the production stage impacts (e.g. Costantini et al., 2021; González-García et al., 2014; Leinonen & Kyriazakis, 2016; Newton & Little, 2018; Pelletier et al., 2013; thinkstep ANZ, 2023; Winther et al., 2020), but is not as important as enteric methane in beef and dairy sectors, and is not applicable to horticultural product sectors.

Thus, LCA has the potential to inform the development of performance-based indicators for agri-food VSS in New Zealand, across life cycle stages and impact categories. However, this development should be informed by sector-specific LCAs to identify the environmental hotspots unique to the supply chains in each sector. These hotspots can then inform development of relevant indicators.

6.2.2.2 Stakeholder influence on product within supply chain (Table 6.1, point 1)

The extent of stakeholder influence over the agri-food product in the value chain could be a key practical determinant when deciding the appropriate system boundary for VSS indicators: it shapes what actors can realistically influence and therefore what indicators are actionable and verifiable. In the New Zealand avocado case study, extending the LCA system boundary beyond the port showed important post-port contributions to the overall life cycle impact. Ripening chambers and transport from the port to retailer materially affected life-cycle impacts, yet it was suggested that these stages be excluded from VSS indicator development because they fall

outside the sphere of influence of New Zealand avocado sector stakeholders (Chapter 4, Section 4.5.1.5).

New Zealand agri-food sectors have different industry structures and product control varies for stakeholders in different sectors. For example, the New Zealand pipfruit (apples and pears) sector is organised similarly to the avocado sector, with a fragmented industry structure compared to sectors like kiwifruit or dairy. The majority of apple and pear orchards are independently owned and packing and postharvest handling are often managed by separate packhouse operators, with different exporters handling the offshore market logistics and distribution (NZ Apples and Pears, 2024). On the other hand, in the kiwifruit industry, Zespri's single-desk marketing model allows coordinated management and control from orchard to logistics and distribution to offshore ports (Robertson, 2023). In the dairy sector, Fonterra has significant influence over New Zealand dairy supply chains to the port through supplier and downstream logistical contracts, quality assurance programmes, and sustainability requirements that shape farm management practices (Fonterra, 2024, 2025).

Further research is needed to develop a better understanding about the degree of influence of different stakeholders in supply chain structures, and how this should be addressed in VSS for different sectors.

6.2.2.3 Nuanced benchmarks for growing regions due to variability (Table 6.1, point 4)

Variability in production systems is a well-documented phenomenon globally (e.g. Astier et al., 2014; Bojacá et al., 2014; Cucurachi et al., 2019; Lam et al., 2021; Nemecek et al., 2023; Notarnicola et al., 2017; Pelletier, 2017; Poore & Nemecek, 2018). However, agri-food VSS do not traditionally consider this variability in their criteria, as identified in Chapter 1, Section 1.4.4. In the avocado LCA, an IQR-based analysis demonstrated notable variability between orchards in the same region as well as between regions in terms of inputs and impacts (Chapter 3, Sections 3.4.1 and 3.4.3). The wide variability is likely influenced by management practices (including fertiliser regimes, irrigation strategies, and agrichemical use) as well as site-specific biophysical factors (e.g. slope of land, soil type and microclimate). For example, the new supra-massive

orchards in the Far and Mid North are more commercially driven than the generational family-owned orchards of the Bay of Plenty. Thus, their management practices are comparatively tailored to more intensive production, resulting in higher impact scores than the Bay of Plenty on average (see Table 3.9). With respect to bio-geophysical differences, to illustrate, the Far North receives far less rainfall than the Bay of Plenty, which relies overwhelmingly on rainfall for water use on the orchard, while the Far North orchards have to be heavily irrigated. This results in the significantly higher average volumetric water use values in the Far North compared with the Bay of Plenty.

These factors also result in variable yields across orchards within and between regions, which consequently influences impact scores per unit output. Yield becomes particularly important when assessing impacts across orchards at different stages of the lives of the trees. Orchard age presents significant differences in impacts per unit of output owing to the lesser yields during the non- and low-production years of the orchard life cycle (see section 6.2.2.4).

These interacting factors show that overarching national-level benchmarks, while suitable for policy-making or longer-term sectoral strategy development, are not appropriate for VSS indicators as they do not represent the geographical, climatic and management practice realities of the three distinct growing regions. They thus highlight the importance of interpreting orchard-level results within a performance-based benchmarking framework that takes all this variability into account rather than relying on single average values. To account for the inter-regional variability specifically, it would be more appropriate to use the regional values as benchmarks for the three regions instead.

Within any region, a tiered benchmarking system could assign orchards to performance categories. Cossu et al. (2023) demonstrated a threshold-based system in their study on developing LCIA-based performance benchmarks for the sheep milk cheese sector in Italy. The best and worst sheep milk cheese production values were presented as the upper and lower thresholds. This resulted in three performance classes – Class A (< than the lower threshold), Class C (> than the upper threshold), and Class B (between the two thresholds). By factoring in

intra-regional variability, this kind of tiered system can encourage continuous improvement for all orchards: higher performers are incentivised to maintain or advance their status, while lower performers are provided with a clear pathway to progress. As Bush and Oosterveer (2015) note, such ‘vertical differentiation’ of standards which move beyond the binary certified/non-certified approach incentivises not just certification, but continuous improvement.

Tiered performance benchmark-based classes are not found in agri-food VSS. However, there are some environmental certification schemes in non-agri-food sectors which use this approach. For example, the building sector has Leadership in Energy & Environmental Design (LEED) in the U.S.A., and the Building Research Establishment Assessment Method or BREEM in the U.K. (BREEAM, 2025; U.S. Green Building Council, 2025). LEED’s tiered performance system awards buildings points across sustainability categories, with the total determining four certification levels – Certified, Silver, Gold, or Platinum – reflecting progressively higher environmental performance. BREEAM’s tiered performance system also assesses a building’s sustainability across multiple categories, assigning a final score that places the project into one of five ratings—Pass, Good, Very Good, Excellent, or Outstanding. An advantage of a tiered system is that it can offer a minimum performance threshold to discourage growers that show little effort towards or outcomes of improvement. For example, if an orchard consistently under-performs and remains in the lowest tier for two consecutive years without measurable improvement, a requirement of remedial actions could be imposed. If that didn’t work, then certification could be withdrawn. Thus, tiered performance classes allow for flexibility and relative benchmarking, while simultaneously offering fixed minimum criteria as well. This offers a more equitable pathway for growers in variable agricultural regions.

With respect to the wider New Zealand agri-food context, a recent study showed regional variations in New Zealand milk production, with Northland having the largest CF due to considerable limitations on pasture production due to climatic and soil conditions (Ledgard et al., 2020). Variability in management practices, inputs and associated environmental impacts are also noted in the literature for kiwifruit, apples, and wine production in New Zealand (Barry,

2011; Gasso et al., 2025; McLaren et al., 2021b; Milà I Canals et al., 2006). McLaren, et al., (2021b) also highlighted the variability in yields for perennial crops due to climatic changes, weather events, diseases, pests, and even biannual bearing. The latter was also an important aspect noted in the avocado LCA study, with significant yield differences observed in alternating years.

Therefore, inter- and intra-regional variability should be considered for all agri-food product sectors when developing benchmarks for sector-wide VSS.

6.2.2.4 Different characteristics of early (and late) years of orchard life cycle (Table 6.1, point 6)

As noted in Chapter 3, Section 3.1.2, published fruit LCA studies generally assess an orchard once it has reached its fully productive state. This approach only presents a partial picture of the full orchard life cycle impacts, given the long lifespans of perennial fruit trees and associated temporal yield variability over the orchard life (Alaphilippe et al., 2016; Cerutti et al., 2011, 2014; Svanes & Johnsen, 2019). The New Zealand avocado LCA study assessed the impact of the non-productive and low-production years of the orchard. The results (Chapter 3, Section 3.4.5) showed that, while productive stages are the largest contributor to whole-of-life orchard life cycle impacts, including the low and non-productive stages increased overall impacts by 13-26% from baseline levels. However, for fully productive orchards, the orchard creation and development stages are in the past. Therefore, including benchmarks for these stages is irrelevant for orchards in full production. This implies that three separate sets of indicators be developed for orchard creation (year 0, no yield), orchard establishment and senescence (years 1-3 and 48-50, low yield), and the productive years (years 4-47, full commercial yield). This is especially applicable in the New Zealand avocado sector, where large commercial orchards are being planted in the Far and Mid North, with plantations expected to be fully productive in the coming years.

Given the low (or no) yields in the non/low production years, a mass-based FU is not appropriate for the orchard creation, and orchard establishment and senescence phases.

Instead, an area-based FU (1 ha of worked avocado orchard) is more suitable (Chapter 3, Section 3.5.2.3). The indicators could be benchmarked against the industry average for existing young orchards in the region using this same area-based FU. Thus, for the avocado sector, an area-based FU should be used for benchmark development for the low and non-productive orchard stages, while the mass-based FU is appropriate for commercially productive years.

Extending this approach to the wider agri-food sector in the country, these suggestions would be suitable for all perennial crops. In their CF update study on these perennial crops, McLaren et al. (2021b) recommend that early and late production stages of perennials should be included in the LCA study (contingent upon the data availability from a range of representative orchards of different ages). This recommendation was based on the specific guideline in the PCR document for fruit and nuts (EPD International, 2019): *'Operations for the initial establishment of the crop including the irrigation system, if its life time is expected to be less than 25 years should be included in upstream processes'*. Moreover, EPD International (2019, Section 4.3.1.1) states that the production of seeds, cuttings or plants for the cultivation should also be included in the upstream processes of the system boundaries. The importance of the nursery stage in LCA studies is often underestimated or even left unacknowledged. As some authors note, plant nurseries can be highly environmentally demanding, in terms of resources, structures and technology (Cerutti et al. 2014; Nicese and Lazzerini 2012). But due to the frequent lack of reliable data for this stage (Graefe et al. 2013; Vatsanidou et al. 2020), it is often excluded from LCA studies. Moreover, the significance of the nursery stage in the context of the whole orchard life is not known for most perennial horticultural crops (McLaren et al., 2021b). Therefore, research needs to be undertaken to determine the environmental impacts of the nursery stage for New Zealand perennial crops.

Regarding other agri-food sectors, for beef cattle and dairy herds the analogous life cycle phases are usually included in LCA studies. For example, the rearing phase before slaughter (cow-calf

stage, backgrounding⁴⁷, breeding herd maintenance) has been shown to contribute significantly to emissions and resource use associated with beef products from beef cattle (Lupo et al., 2013; Putman et al., 2023). Similarly, in the dairy sector, heifers have to be raised for approximately 2 years before first calving and producing milk (Ledgard et al., 2021), and replacement herd maintenance is also an important aspect in dairy LCAs (e.g. Chobtang, 2016; Galloway et al., 2024; McGeough et al., 2012).

Thus, for the New Zealand agri-food sectors where production-related life cycle stages are important, indicators for a VSS should include consideration of all these stages, rather than just the commercially productive stages. Moreover, an alternative FU based on area is more appropriate for indicator development focused on the low- and non-productive life cycle stages of an orchard.

6.2.2.5 Site-specific characterisation factors for water use (Table 6.1, Point 2)

In the avocado LCA study, water use was assessed using the AWARE method (Chapter 3, Section 3.2.2 and Chapter 4, Section 4.5.2.2). This method provides three-tiers of site-related characterisation factors for water use impacts: 1) national level, unspecified factors, 2) sub-national (regional) factors disaggregated by use type (agricultural and non-agricultural), 3) watershed-level factors. Use of factors at more aggregated spatial levels are associated with a concomitant increase in uncertainty in the results (Boulay & Lenoir, 2020). For example, in New Zealand, the national level unspecified factors are higher than all the sub-national factors except the sub-national agricultural value for Canterbury. Thus, if avocado production in the Bay of Plenty (which has one of the smallest sub-national characterisation factors in New Zealand) is assessed using the national level factor, the Bay of Plenty impact value would be misleading. Thus, geographically-specific characterisation factors should be used for activities instead of the

⁴⁷ Backgrounding refers to the practice of raising weaned calves in a period between weaning and finishing in a feedlot (North Dakota State University, 2025). During this phase, calves are fed diets rich in forage—with or without supplemental grain—and allowed to gain weight and adapt prior to placement in intensive finishing systems.

national-level factor. An alternative, in the absence of data on geographical locations, is to use volumetric water use as an indicator.

This issue is also relevant for other agri-food sectors in New Zealand. For example, Herath et al. (2013a,b) highlighted the large variation in inter-regional water consumption values in New Zealand wine production due to varying climatic and soil profiles of the regions. The authors advocated water use assessments at a local level with spatially resolved inventory data. With respect to the beef and dairy sectors, the importance of site-specific characterisation factors to avoid over/under-representing impacts has been highlighted in some studies (Higham et al., 2024; Zonderland-Thomassen et al., 2014; Zonderland-Thomassen & Ledgard, 2012). For example, Canterbury is New Zealand's most intensively irrigated region, and 64% of the irrigated land area is associated with dairy farming (2022 data in Stats NZ, 2024). As noted earlier, the AWARE sub-national agricultural characterisation factor for Canterbury is higher than the national level (unspecified) characterisation factor and so should be used for assessing water use in dairy farming for the Canterbury region.

This research thus highlights the importance of using water scarcity indicators that are as site-specific as possible when developing water use indicators for sector-wide VSS in New Zealand.

6.2.2.6 Performance metrics for ecotoxicity assessment (Table 6.1, Point 5)

The avocado LCA study results identified fertiliser and agrichemical manufacture (and their transport to the orchard) as the main ecotoxicity (freshwater and terrestrial) hotspots at the orchard stage (Chapter, Section 3.5). At the same time, key methodological challenges were identified related to the accuracy of LCIA methods to evaluate ecotoxicity impacts on agricultural soil. The first related to the proportion of pesticide emissions reaching different environmental compartments; the lack of consensus about this aspect has resulted in varying assumptions about the ratio of emissions reaching the different environmental compartments (air, water soil etc.) when modelling agricultural systems (Fantke, 2019; Rosenbaum et al., 2015). The most widely used approaches in agricultural LCAs base their models on the assumption that 100% of the applied pesticides (AIs) are emitted directly to agricultural soil

(Barizon, 2021; Fantke, 2019; Nemecek et al., 2020, 2022; Nemecek & Schnetzer, 2012; Picoli et al., 2018; Renaud-Gentié et al., 2014; Rosenbaum et al., 2015). Moreover, EPD International (2019) also states, *'If no specific data are available, it shall be assumed that all pesticides applied are 100% emitted to agricultural soil'*. In keeping with these guidelines, it was assumed for this LCA study that 100% of the emissions from all applied insecticides, herbicides, and mineral oil were emitted to agricultural soil. However, this does not accurately represent the reality of pesticide emissions to the different environmental components. This has been the centre of ongoing research on emission and toxicity modelling methods in LCA, in particular, the 'Operationalising Life Cycle Assessment for Pesticides (OLCA)' project which ran from 2017-2022 (Nemecek et al., 2022). Post-completion, OLCA's PESTLCI Consensus model includes emissions to different environmental compartments – air, field soil surface, field crop leaf surface, and off-field surfaces and has been incorporated into the latest version of the Swiss Agricultural Life Cycle Assessment (SALCA) method as well, replacing the previous version's guideline of 100% emission to agricultural soil (Nemecek et al., 2023).

A second issue relates to the ongoing debate about the most appropriate boundary between the technosphere and ecosphere for agricultural systems⁴⁸. For example, early research on harmonising LCA models in agriculture included agricultural soil (up to the depth of the water table) within the system boundary (Audsley et al., 1997). However, unlike traditional industrial systems, agricultural systems are more complex with biological aspects that intersect the technosphere and ecosphere (Notarnicola et al., 2015). Therefore, the boundaries in agricultural systems are less easily defined (van Zelm et al., 2014, Rosenbaum et al., 2015, Notarnicola et al., 2017). The difference in approaches to delineate boundaries between the technosphere and the

⁴⁸ The technosphere refers to all anthropological activities and processes involved with the product system, whereas the ecosphere refers to everything 'environmental' or 'natural' which lies beyond the boundary of the technosphere. Emissions from the technosphere which cross the boundary to the ecosphere impact ecosystems and human health, whereas resources obtained from the ecosphere to fuel processes in the technosphere affect resource availability (Hauschild et al., 2018, p. 78).

ecosphere (and the related decision regarding whether to include agricultural soil in the technosphere or not) also affects the fate assumptions of pesticide emissions. For example, although the PESTLCI 2.0⁴⁹ methodology (Dijkman et al., 2012) has been regarded as one of the more accurate emission modelling approaches (PESTLCI Consensus was based on the PESTLCI 2.0 emission quantification model), it considers the agricultural field (to a depth of 1m and 100m of the air column above ground) to be a part of the technosphere, and therefore, does not consider soil in the agricultural field to be an environmental compartment for emissions (Birkved & Hauschild, 2006; Renaud-Gentié et al., 2014; Rosenbaum et al., 2015). This means that, using the PESTLCI 2.0 approach, the fate of most of the emissions is degradation or crop uptake, with only a small fraction crossing the system boundary into the environmental compartments beyond the agricultural system)– and no assessment of the fraction that reaches, and remains in, agricultural soil⁵⁰. This issue around system boundaries also follows on to the methods used to model terrestrial ecotoxicity impacts. In this study, the ReCiPe 2016 midpoint (H) method was used, but like other LCIA models, it too considers agricultural soil to be part of the technosphere, and therefore only models impacts on industrial soil as part of the terrestrial environment (Huijbregts et al., 2017). This is a key methodological limitation when assessing the ecotoxicity impacts associated with use of pesticides. For the New Zealand avocado LCA study it meant that the terrestrial ecotoxicity impacts from agrichemicals were mainly associated with the pesticide manufacturing process, particularly copper-based fungicide

⁴⁹ PEST LCI 2.0 is a more thorough approach accounting for several localised post-application fate pathways of pesticides, classified into primary (wind drift and deposition on soil and leaves) and secondary (distribution processes, taking into consideration (volatilisation, degradation, uptake by leaves, run-off, and leaching). However, with regards to this study, one of the drawbacks of the PEST LCI 2.0 method is that it is Europe-centric (Dijkman et al., 2012) and therefore would not be representative of New Zealand conditions.

⁵⁰ The PESTLCI Consensus model is more inclusive, as it provides for emissions to four environmental components, including agricultural soil (Nemecek et al., 2022). However, the decision on whether to include agricultural soil as part of the technosphere or ecosphere is subject to the goal and scope of the study, and consequently can influence the final results (Barizon, 2021).

manufacturing. This was relevant in part due to the sector's focus on copper-based fungicides – however, their main concern was contamination of avocado orchard soil with copper applied in fungicides rather than manufacturing-related impacts. Copper application on orchards is widely recognised as an environmental issue, particularly with respect to impacts on soil microbiome and health (Matse et al., 2024; Merrington et al., 2002; Van Zwieten et al., 2004) – however, the current study could not model these impacts effectively due to the above-mentioned reasons. With respect to improved modelling of pesticide flows to different environmental compartments post application (rather than 100% to agricultural soil), there are certain tools which, in theory, could provide detailed agrichemical flows to different environmental compartments in New Zealand. The GROWSAFE calculator is a New Zealand-based ecotoxicity assessment tool which provides advice as to relative risk of pesticide leaching in the short term as well as accumulation in soil in the longer term. It is based on SPASMO (Soil Plant Atmosphere System Model), which is a mechanistic model that considers the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, run-off and drainage) of water from the soil profile. However, these tools do not run on generic assumptions; they require detailed inputs including daily climate data, layered soil profiles for each orchard, irrigation schedules, canopy and rooting details, and complete pesticide spray diaries with timing information – all of which could not be accessed within the time and scope limitations of this PhD research. That said, if such detailed input data were available, incorporating these methods could allow more New Zealand-specific ecotoxicity modelling incorporating a wide range of pesticides and strengthen future iterations of this research.

In the absence of access to such detailed modelling, additional indicators to represent the soil ecotoxicity associated with use of agrichemicals in orchards should be developed for a VSS for the avocado sector. In developing indicators for a VSS, a newer LCA ecotoxicity assessment method (such as PESTLCI Consensus) that accounts for emissions to the different environmental components should be used, and it should also be aligned to New Zealand conditions. Furthermore, the LCI method would also need to be combined with a suitable LCIA method capable of assessing terrestrial ecotoxicity impacts on agricultural soil (i.e. by considering it to

be a part of the ecosphere). In the absence of such toxicity assessment methods, other non-LCIA-based performance metrics should be included in a VSS to represent ecotoxicity impacts on agricultural soil. As a default, simple input metrics such as ‘quantity of fungicide or AI applied per hectare annually’ could be used. Another simple alternative way to indicate ecotoxicity risk is to use New Zealand’s Hazardous Substances and New Organisms (HSNO) hazard classes by adding up how much pesticide is applied that is classified as harmful to soil, water, animals, or insects. For each orchard, this means summing the kilograms of active ingredient per hectare per year within each relevant HSNO class (for example, soil ecotoxicity classes 9.2A–C) to produce a single load indicator.

These insights are equally relevant for other agri-food sectors in New Zealand that use pesticides.

In summary, to address methodological challenges posed by current approaches for ecotoxicity assessment of agricultural soil, newer and more appropriate assessment methods (for estimating emission fractions to multiple environmental components and assessing terrestrial ecotoxicity impacts on agricultural soil) should be used. In the absence of such indicators, simple performance metrics could be included to represent impacts on agricultural soil.

6.2.2.7 Non LCIA-based indicators (Table 6.1, Points 5, 7, and 8)

The avocado LCA study showed that characterised impact category indicators may not always be the best indicators for use in a VSS. Two examples are airfreighting of avocado to export destinations (Section 6.2.2.1), and orchard ecotoxicity assessment (Section 6.2.2.6). An additional point is that communication of LCA results remains a challenge (Galindro et al., 2019). LCIA metrics can be technical and abstract, making them hard for producers and supply chain actors to interpret in practical terms. For example, a grower may not intuitively connect “kg PO₄ eq./kg fruit” (eutrophication potential) with their day-to-day operations, even though the metric is scientifically meaningful. By contrast, input-based indicators such as ‘kilograms of phosphate fertiliser applied per hectare’ are more tangible and directly linked to operational decisions. These are easier for practitioners to interpret, monitor, and improve over time. For

example, in the avocado LCA direct water use on orchard was the main contributor to overall water use impacts at the orchard stage. While the characterised water use impact can be used as an indicator, it may be more effective to use on-orchard volumetric water use for this purpose as it is directly under the control of growers.

With respect to the wider agri-food sector, individual sectoral LCA studies are needed to prioritise development of performance-based indicators targeted on sector-specific environmental hotspots. These indicators also need to be capable of supporting continuous improvement at the stakeholder level. For example, Ireland's Origin Green scheme requires farmers to report key aspects of their on-farm activities e.g. fertilizer usage, feed management, manure application, and energy use, which are then used to generate CF reports for individual farms showing contributions from key sources such as fertiliser use, energy consumption, feed, and livestock (Bord Bia, 2021, 2023). The disaggregation of GHG emissions into key sources enables each farmer to identify their main sources of impacts and develop appropriate mitigating activities. Similarly, SWNZ provides members with annual sustainability scorecards, including metrics related to GHG emissions, waste, water, plant protection, air pollution, and soil health (NZ Wine, 2020). These reports highlight key inputs contributing to environmental impacts, supporting the identification of targeted efficiency measures in vineyard and winery operations. Bonsucro-compliant growers and millers are required to measure their GHG emissions using the Bonsucro calculator – the results are made available on a dashboard which shows producers their GHG emissions by activity type and scope, highlighting areas for priority action (Bonsucro, 2025). These VSS operators also use the collected producer-level carbon footprint (and other input) data to calculate sectoral trends and averages at regular intervals, which enables producers to benchmark their performance against peers.

Thus, an integrated approach using both LCIA-based indicators and selected activity-level metrics may be most effective for VSS indicator development based on LCA studies. The choice of which indicator to use will depend on individual LCA studies of each sector. In general, use of both types of indicators, in conjunction with benchmarking, will support development of a VSS

that is meaningful to key stakeholders whilst also being based on robust, scientifically rigorous and life cycle-oriented environmental analysis.

6.3 Role of LCA in informing consumer decision-making in New Zealand based on the combined nutritional value and environmental impacts of food

6.3.1 Implications of use of nLCA to inform consumer decision-making

Conventional LCA typically uses FUs based on mass or volume and thus overlook food's primary role which is to provide nutrition. Nutrition-focused research, conversely, evaluates health benefits but rarely accounts for environmental costs. Considering either dimension in isolation produces a fragmented understanding of food system sustainability and limits the ability of consumers, policymakers, and industry to make informed choices.

Nutritional LCA (nLCA) was developed to bridge this gap by recognising nutrition as food's core function and explicitly incorporating nutrition into LCA. Early nLCA applications assessed only a narrow set of individual nutrients (Martínez-Blanco et al., 2011; Oonincx & de Boer, 2012; Saarinen et al., 2017; McAuliffe et al., 2018); however, foods comprise complex combinations of macro and micronutrients. Therefore, focusing on individual nutrients under-represents the true nutritional value and health impacts of food. As discussed in Chapter 5, Section 5.1, while NRF_{9.3} is one of the most commonly used nutrient profiling (NP) indices, it excludes certain key nutrients considered beneficial to health. To address such omissions, some researchers propose expanding indices or tailoring them to specific food groups (Hallström et al., 2019; Bianchi et al., 2020). Research is ongoing to address key methodological questions in developing such indices, such as choice of nutrients and FU, whether to weight or cap nutrients, and how to represent adverse nutritional aspects. In addition to these methodological questions, a limitation of current nLCA research is the focus on individual foods or entire diets, with relatively few applications at the meal level. Yet meal-based analysis is especially relevant because it aligns closely with many decisions made by consumers related to food consumption (Takacs et al., 2022; Mazac et al., 2023; Sameshima et al., 2023).

This study addressed these gaps by applying NRF indices in a meal-level nLCA using a New Zealand case study of simple ‘toppings on toast’ (ToT) meals. It used the NRF_{9.3} index and a customised expanded index (NRF_{28.3}) to rank meals based on combined nutritional and environmental aspects. Rankings were compared using three additional FUs (serve size, 100 g and 100 kcal).

It was found that use of an expanded NRF index did not substantially alter the meal rankings. When differences occurred, they were mainly due to added micronutrients, and in some cases mono-unsaturated fats. The choice of FU affected absolute values but had little effect on the relative ranking of meals (Chapter 5, Sections 5.3.1.3 and 5.3.2).

The main insights from this research about the use of nLCA for meal-level comparisons within the New Zealand context are summarised in Table 6.2. It should be noted that these insights and their implications are based on some important assumptions:

- In the absence of up-to-date data on nutritional intake for New Zealand residents, data for adult nutrition intake from 2008/09 (University of Otago & Ministry of Health, 2011) had to be used.
- Serve size data was obtained from the New Zealand food composition database (New Zealand Food Composition Database (NZFCD), 2022). However, portion sizes vary widely amongst individuals, and this was not considered in this research.
- Nutrient bioavailability was not addressed due to data unavailability.
- The nLCA study focused only on climate change as the environmental impact indicator; incorporation of additional impact category results might produce different results.

Table 6.2 Insights from nLCA study and their implications for use at the meal level in the New Zealand context

<i>Topic</i>	<i>Insight and implication</i>	<i>Thesis chapters and sections</i>
1. Choice of nutrients in index	Insight: Including additional nutrients changed the nLCA values of individual toppings but did not alter the meal rankings significantly. When the rankings did change, it was due to water soluble vitamins and in some cases, unsaturated fats in the expanded index. Implication: Research on other meals is needed to further investigate the influence of choice of nutrients in index. Based on the (outdated) survey and this nLCA study, use of the NRF_{9.3} index with two additional unsaturated fats (MUFAs and PUFAs) may be appropriate for the New Zealand context. The nutrition survey needs to be updated to reflect current scenarios.	Chapter 5, Section 5.3.1.3
2. Choice of FU	Insight: Choice of FU (mass-, energy, or serve-based) did not substantially alter the relative ranking of the examined foods. Implication: Research on other meals is needed to further investigate the influence of choice of FU. For the New Zealand context a pragmatic approach could be to present nLCA results using FUs based on both energy contribution and typical serving size. Portion size adjustments should be applied if standardised data are available.	Chapter 5, Section 5.3.2
3. Indicators for communicating nLCA results to consumers	Insight: The quantile-based approach can be used to communicate nLCA results to consumers – but results need to be recalculated if there are significant/frequent changes in the studied meals. The presentation style should be adapted for different stakeholder groups. Implication: Presentation styles for results should be targeted to different audiences including: 1) a simple colour coded traffic light type of label based on quantile categories and grades (A-D) for quick guidance; 2) optional allowance for separate weighting of nutritional and environmental results to further support individual consumer choices; 3) a color-coded table representing the nLCA results at midpoint for consumers/customers who want detailed nutritional and environmental performance information.	Chapter 5, Section 5.4.1.4
4. Use of weighting	Insight: Weighting of individual nutrients is an important consideration for nLCA approaches, especially in specific target populations with specific dietary/nutritional requirements Implication: Updated information on nutritional inadequacies in New Zealand is needed. In the meantime, nutrients should be weighted equally in New Zealand nLCA applications.	Chapter 5, Section 5.4.1.3

5. Use of capping	Insight: Capping nutrients in nLCA indices is an important methodological choice, especially when applied to a broader range of meals. Implication: Further research is needed to understand the health implications of exceeding RDIs. Nutrients with demonstrated health benefits at higher-than-RDI intakes could be left uncapped to reflect their contributions to health outcomes.	Chapter 5, Section 5.4.1.3

The insights from this study are further discussed in section 6.3.2 with respect to methodological adaptation and applicability to the New Zealand context.

6.3.2 Discussion on insights from nLCA study

6.3.2.1 Choice of nutrients in NRF index (Table 6.2, Point 1)

Two NRF indices were used in the nLCA study: the widely used NRF_{9.3} and the customised NRF_{28.3}. The results showed that including additional nutrients changed the nLCA values of individual toppings but did not alter the meal rankings significantly (Chapter 5, Section 5.3.1.3). This indicates that an index with a limited number of toppings like NRF_{9.3} may be sufficient to provide representative meal ranking outcomes. Other studies have suggested this as well (Fulgoni et al., 2009; Drewnowski, 2017; Green et al., 2020; Weidema and Stylianou, 2020).

At the same time, the results of this study also showed that while an expanded index did not alter meal rankings much, when the rankings did change, it was due to water soluble vitamins and in some cases, unsaturated fats (Chapter 5, Section 5.4.1.1). However, this insight is meaningful only in the context of nutrient inadequacies within a target population. For example, if a section of the population is deficient in niacin or folate, then an expanded index which includes these water-soluble vitamins would be more meaningful to address those nutritional inadequacies. The last nutrition survey in New Zealand was conducted in 2008/09 (University of Otago & Ministry of Health, 2011) and included several key nutrients, but two water soluble vitamins (folate and pantothenic acid) as well as vitamins K and D, and trace minerals like copper, chromium, and iodine, were excluded⁵¹. The report noted no significant Estimated Prevalence of Inadequate Intake (EPII) of vitamins that were included in the survey. With respect to fats, the nutrition survey report stated that saturated fat contributed 13% of the total

⁵¹ Selenium intake was considered inadequate for both male and female adults in the New Zealand nutrition survey. While minerals contributed relatively less to the nutritional score of the NRF_{28.3} index compared to water soluble vitamins, it illustrates the bearing that an expanded index could have with respect to specific target populations and their nutritional inadequacies.

energy requirement in New Zealand adults – this is above the recommended cap of 10%. Many national and international nutrition guidelines recommend replacing trans and saturated fats with foods high in monounsaturated (MUFAs) and polyunsaturated fats (PUFAs), particularly omega-3 and omega-6 fatty acids, due to their documented health benefits (National Health and Medical Research Council, 2013; Ministry of Health, 2020; World Health Organization, 2023; Mozaffarian et al., 2010; Ravaut et al., 2021). Green et al. (2020) also points out that failing to account for these beneficial fats can unfairly disadvantage foods that are rich in them. Given the importance of unsaturated fats in improving health, inclusion of MUFAs and PUFAs in the NRF_{9.3} index (i.e. creating an NRF_{11.3} index) should be considered.

Thus, choice of nutrients in an NRF index is an important consideration when applying the nLCA method developed in this study. This choice should be guided by the nutritional requirements of the target population, but the last New Zealand nutritional survey is outdated and omits information on several significant nutrients. Based on that outdated survey and this nLCA study, use of the NRF_{9.3} index with two additional unsaturated fats (MUFAs and PUFAs) may be appropriate. However, further research (using updated nutrition intake data when available) should be undertaken to corroborate the results of this study.

6.3.2.2 Choice of FU/reference unit (Table 6.2, Point 2)

The findings of the nLCA study showed that the choice of FU (reference unit) – whether mass-, energy, or serve-based did not substantially alter the relative ranking of the examined foods (Chapter 5, Section 5.3.2). However, mass-based FUs fail to capture the nutritional purpose of food consumption and risk distorting comparisons in consumer-oriented applications (Green et al., 2021; Sonesson et al., 2017). On the other hand, energy-based FUs adjust for variable calorific densities of different food items and therefore can make it possible to calculate nutritional value (in terms of energy) of food, independent of portion or serve size (Drewnowski, 2005; Fern et al., 2015; Schaubroeck et al., 2018). Although some argue in favour of using such energy-based metrics (e.g. Green et al., 2023), they still do not account for the

other nutritional functions of food, apart from dietary energy. Of the three FUs, serve sizes most closely reflect what people consume in a meal context, and researchers have argued that standardized serve sizes could become the 'preferred' functional unit for nLCA studies (e.g. Bianchi et al., 2020). A key limitation is that, although foods within a single category often have comparable serve sizes typically standardised according to the energy they provide (see for example, Hallström et al., 2019 in their study on seafood), serve sizes are generally inconsistent across different food groups within a meal, making cross-food comparisons more complex.

In the New Zealand context, standardised serve sizes are provided by the national food composition database (New Zealand Food Composition Database (NZFCD) 2022). However, these are not legally standardised like the U.S. Reference Amount Customarily Consumed (RACC) mandated by the Food and Drug Administration (FDA) (Berardy et al., 2019; Drewnowski, 2017; Grigoriadis et al., 2021). For the New Zealand context therefore, a pragmatic approach could be to present nLCA results using FUs based on both energy contribution and typical consumption quantities.

Another point in this discourse is that even serve-based FUs do not resolve the challenge of portion sizes, i.e., the discrepancy between the standardised serve and the actual quantity consumed in practice (Livingstone & Pourshahidi, 2014). Thus, while FUs can provide consistency for comparisons, portion sizes reflect behavioural realities that may ultimately shape the environmental consequences of diets. Therefore, future applications of this approach to consumer communication in New Zealand may need to consider both dimensions: the standardised FU as a benchmark for fair comparison, and portion size adjustments to capture real-world consumption.

Taken together, these reflections suggest that, although the choice of FU did not drastically alter the relative rankings of foods in the nLCA study reported in Chapter 5, it may be more significant in other analyses. For the New Zealand context, calculation of both energy- and

serve-based FUs offers a pragmatic way forward until more robust serve-based FUs are available.

6.3.2.3 Indicators for communicating nLCA results to consumers (Table 6.2, Point 3)

In the nLCA method developed in this study, a quantile-based system was used to present the nLCA results (Chapter 5, Section 5.3.1.3). The quantile-based approach to enviro-nutritional ranking has been used in other studies as well (e.g., Bianchi et al., 2020; Strid et al., 2021; Green et al., 2023). The limitation of this approach is that quantiles are directly based on the included datasets in a study. Thus, ranking is determined by the meals studied in the nLCA; any addition, deletion or replacement of meal options may require recalculation of the quantiles. This methodological challenge should be evaluated in the context of specific application areas. If applied to a limited range of meals that does not change frequently (e.g. in restaurants, hospitals, or schools), the quantile-based approach can be based on one set of calculations. However, where the meal options are frequently altered, the results would have to be recalculated each time to account for additional food items and maintain equal numbers of food items in each quantile.

With respect to presenting the nLCA results to consumers, two approaches are proposed: 1) use a colour-coded table based on quartile-categorised nLCA values of the meals (NRF, NRn, LIM, GWP, and ED), thereby presenting environmental and nutritional dimensions separately; and 2) ranking the foods using an integrated indicator based on values assigned to nutritional and environmental parameters. Presenting disaggregated indicators in parallel allows important trade-offs to remain visible, for example where a meal may be highly nutrient-dense but only moderate in environmental performance, or conversely, environmentally low-impact but more modest nutritionally. This approach therefore retains scientific nuance and avoids implying that one dimension inherently dominates the other. However, presenting the results in a table as an extensive list of numbers could be difficult for users/consumers to understand. The results aggregated into a single score can more easily highlight the better options in the range of meals

and reduce cognitive load at the point of decision-making (Schaubroeck et al., 2018). Several consumer-facing food rating labels like France's Planet-Score and Eco-Score, Europe's EnviroScore, U.K.'s Eco-Impact, and the Swiss Eaternity food score take this approach, using stars or grades to rate food products (Deconinck & Hobeika, 2023; OECD, 2022; WBSCD, 2021). However, collapsing multiple dimensions into a single score reduces nuance; for example, a meal with excellent nutritional quality but moderate environmental impact may receive a middle grade, masking the underlying trade-off. Thus, it is important to find a balance between scientific accuracy and consumer understanding and usability. One approach could be to use the single score rankings for quick guidance and in addition offer the table to consumers interested in additional details. Further, alternative rankings based on different weightings applied to nutritional and environmental indicators could be made available to offer more nuanced information to consumers.

In summary, the nLCA results for different meals can be presented either using indicators in parallel in a quantile-categorised colour-coded table showing disaggregated results or by integrating environmental and nutritional parameters into a single score-based graded system. It is important to present these nLCA results to consumers to allow for easy decision-making without eroding scientific accuracy.

6.3.2.4 Weighting in nLCA (Table 6.2, Point 4)

Most nLCA studies exclude a specific weighting process, i.e., they weight all the nutrients equally due to a lack of scientific consensus on the appropriate criteria to use for this purpose (Drewnowski, 2017; Green et al., 2020). For the same reason, no weighting was applied to the nutrients in this nLCA study Chapter 5, Section 5.4.1.3. In the New Zealand context, the Adult Nutrition Survey conducted in 2008/09 provide some data about EPII for 12 nutrients, which could theoretically underpin a scarcity-weighted index. However, as mentioned in section 6.3.2.1, this dataset is now over 15 years old and excludes key nutrients of interest for NRF indices, such as vitamin D, folate, pantothenic acid, vitamin K, copper, chromium, and iodine

(University of Otago & Ministry of Health, 2011). Given that dietary patterns and nutrient adequacy evolve over time, reliance on outdated or incomplete survey data is likely to misrepresent current nutritional priorities in New Zealand. Until such data become available, equal weighting of nutrients should be used for nLCA in New Zealand.

The environmental and nutritional dimensions were equally weighted in this nLCA study. However, consumers may attach different levels of importance to these two aspects. In order to account for a diversity of perspectives, a simple slider tool could be made available online as part of an enviro-nutritional assessment tool to enable variable weighting of the two dimensions.

With respect to environmental indicators, only one impact category (climate change) was considered in this study. However, if the method is expanded to include other categories as well, then weighting across different impact categories is required in order to rank food items. Again, this can be addressed using the slider-based approach noted above.

Thus, weighting of nutrients, nutritional/environmental dimensions relative to each other, and different impact categories requires consideration when undertaking nLCA studies. For nutrients in the New Zealand context, equal weighting of nutrients is recommended pending updated information on nutrient scarcity/inadequacy in the population. With respect to the other two aspects, allowing for consumers to choose their weighting preferences using a slider tool or equivalent could be a meaningful way to facilitate consumption choices.

6.3.2.5 Capping nutrients (Table 6.2, Point 5)

The issue of nutrient capping (i.e. restricting “good” nutrients to 100% of their recommended daily intake (RDI)) remains a topic of debate in nLCA studies. Some researchers argue that, at the level of individual food items or simple meals, nutrients should remain uncapped because a typical diet includes diverse foods that compensate for variations in nutrient diversity (Hallström et al., 2018; Mazac et al., 2023). In the present study, none of the nutrients exceeded

their RDIs per serving, making capping unnecessary Chapter 5, Section 5.4.1.3. However, when applying nLCA methods to a broader range of meals in New Zealand, this issue may be relevant.

The decision to cap or not cap nutrients should be guided by the health implications of exceeding RDIs. Conversely, nutrients with demonstrated health benefits at higher-than-RDI intakes, such as omega-3 fatty acids, dietary fiber and selenium (National Medical Health and Research Council, 2017) could be left uncapped to reflect their contributions to health outcomes. Further research is needed to test out the idea of integrating both capped and uncapped nutrient scores into nLCA.

6.4 Implications of research for SCP in New Zealand

6.4.1 Implications for government policy

6.4.1.1 *Sustainable production for New Zealand agri-food sectors*

The LCA-based indicators defined in this research can be used in development of a VSS to quantify and benchmark environmental impacts for the avocado sector. This initiative could additionally support existing sustainable production policies. For example:

- The **Primary Sector Growth Fund (PSGF)** is a government co-investment initiative designed to foster innovation and enable economic benefits for New Zealand's food and fibre sectors (MPI, 2025). The PSGF functions as a policy tool by directing funding toward projects that deliver measurable economic outcomes via projects that span economic, environmental, social, and/or cultural bases. Thus, in principle, it could be used to support further development and implementation of a sector-wide VSS, which could also be expanded to include the horticultural industry or even other primary industries.
- Under the **Zero Carbon Act (Climate Change Response Act 2002, amended 2019)** (MfE, 2021), New Zealand is required to reduce net GHG emissions (excluding biogenic methane) to zero by 2050. LCA-based VSS offer a pathway to monitor and report emissions at the

product or farm level (or even supply chain level), complementing national reporting requirements.

- **Farm Environment Plans (FEPs)** are a regulatory tool in New Zealand designed to help farmers identify and manage environmental risks on their land. Mandated under the Resource Management Act and reinforced by regional councils, FEPs are increasingly required for sustainably managing soil, water, and nutrients (Canterbury Regional Council, 2024; Gisborne District Council, 2021; Greater Wellington Regional Council, 2025; Real Estate Authority, 2020; Waikato Regional Council, 2020). Unlike FEPs, which are farm-specific, largely practice-driven and compliance-oriented, VSS utilise continuous improvement performance metrics that can be used for ongoing benchmarking across farms and supply chains. For example, instead of only requiring farmers to adopt practices like nutrient or irrigation management plans or riparian buffers, councils could require reporting of emissions intensity per unit of production. From a policy perspective, it would bridge between private standards and public regulation and provide a pathway for farmers to meet regulatory expectations more efficiently. Moreover, it would allay concerns about duplication of compliance standards and associated administrative and financial burdens, which were noted by stakeholders as a barrier for uptake of a potential VSS scheme in the avocado sector (Chapter 2, Section 2.4.2).
- New Zealand has a **green public procurement (GPP)** policy framework (New Zealand Government Procurement, 2025). Uptake of LCA-based agri-food VSS can be incentivised by prioritising or mandating public sector organisations to procure food that is certified to an LCA-based VSS.

The examples above indicate how an LCA-based VSS can be integrated with a range of SCP policies in New Zealand to support efficient delivery of desired outcomes. This may also be advantageous for exported agricultural products if a New Zealand VSS is recognised internationally – hence, it is important for such a VSS to be based on criteria/indicators aligned

with international standards, as was demonstrated in this research which followed international LCA standards and guidelines like ISO and EPD.

6.4.1.2 Sustainable consumption for New Zealand consumers

For New Zealand, examples for applying the nLCA research in this thesis to policy include:

- The **New Zealand Food Composition Database (NZFCD)** is the country's most comprehensive source of nutrient information on >2800 foods commonly eaten in New Zealand (Bioeconomy Science Institute, 2021; NZFCD, 2022). The database informs multiple layers of nutrition research, policy, education, and public health initiatives as well as trade labelling and declarations for exporters (MBIE, n.d.). As the database currently provides nutritional composition only for individual foods, there is an opportunity to integrate environmental indicators alongside the existing nutritional ones in any future updates. This would ensure that the database makes the fundamental data available for users to develop their own indices and applications. An additional extension could be the inclusion of standard composite meal rankings (such as common breakfasts or canteen lunches) using nLCA.
- Current **New Zealand dietary guidelines** (Ministry of Health, 2020) do not address environmental sustainability. A recent study noted that while national food based dietary guidelines (FBDGs) are beginning to incorporate considerations of the relationship between diets and environmental sustainability, this material is often confined to technical or background reports rather than the consumer-facing guidelines (James-Martin et al., 2022). Moreover, the themes most frequently highlighted (the balance of animal- and plant-based foods, biodiversity, and food loss and waste) tend to be addressed just in broad and aspirational terms. There is an opportunity for the nLCA method developed in this research to support development of FBDGs that explicitly link dietary choices with environmental sustainability, and translate these principles into clear, actionable, and specific advice for consumers (James-Martin et al., 2022).

- With respect to **GPP related to food provision**, this is applied through programme- and sector-specific policies rather than a single, cross-government food procurement standard. For example, the Ministry of Education's Ka Ora, Ka Ako (Healthy School Lunches) programme (Ministry of Education, 2025b) facilitates GPP principles through a focus on sustainability and waste reduction within the programme. Specifically, the programme requires suppliers to prioritise recyclable packaging, manage waste effectively, and report on waste sent to landfill (Ministry of Education, 2025a). The results of nLCA studies could be used to identify meal options that are optimal from both a nutritional and environmental perspective, and to support procurement policies for schools and other government-operated institutions (e.g. hospitals, government departments, and aged care centres).

Beyond these examples, a government driven website or app offering consumer-facing meal planning guidance and resources based on nutritional *and* environmental concerns could also be developed. For example, the United States Department of Agriculture's (USDA) 'My Plate' website is a public health tool which helps people build meals and recipes aligned with the MyPlate food group proportions (based on the Dietary Guidelines for Americans) (U.S. Department of Agriculture, 2023). It also contains a tool which generates personalised daily food groups targets and a set of sample meals and recipes which can be used to meet those targets. A similar public sector tool could be designed for New Zealand incorporating both nutritional and environmental dimensions using the nLCA method.

6.4.2 Implications for industry

6.4.2.1 Sustainable production for New Zealand agricultural sectors

The research on avocado grower perceptions (Chapter 6, Section 2.4.1) identified that growers were motivated and proactive about voluntary sustainability initiatives. They viewed Global G.A.P. certification, on the other hand, as time- and cost-intensive with heavy administrative burdens, and were therefore averse to additional compliance requirements that would add to these burdens. However, at the same time, they did not view G.A.P. indicators as comprehensive

in terms of environmental issues and also criticised its 'tick box' practice-based approach to sustainability. Instead, they supported use of performance indicators that enabled the sector to measure its impacts and use quantitative data as a baseline for continuous improvement. Therefore, instead of setting up a separate avocado orchard VSS, it may be advisable instead to incorporate orchard-stage LCA-based indicators into the NZGAP certification scheme (the national level G.A.P. certification benchmarked to Global G.A.P.).

With respect to the wider avocado supply chain, the LCA results showed that the post-harvest stages made a notable contribution to the assessed environmental impacts (Chapter 4, Section 4.4.1). Therefore LCA-based indicators should be applied to the post-harvest stages as well. As neither Avogreen or Global G.A.P. address these stages of the life cycle, a separate VSS would need to be developed for this purpose.

Stakeholders in the avocado supply chain expressed a preference for a horticulture-wide life cycle-based VSS that could present a unified sustainability story. This could be started as a pilot programme in the avocado sector and then expanded to other horticultural sectors. Ireland's Origin Green programme is an example where this has been done, and Lees (2020) specifically calls for a nation-wide programme like Origin Green for New Zealand.

6.4.2.2 Communicating information about sustainable consumption for New Zealand food companies

With respect to the meal-level nLCA method developed in this study, it has several potential applications to support more sustainable food consumption:

- **Restaurants and cafés:** nLCA results could be used as indicators on menu items to communicate information to customers about their enviro-nutritional performance.
- **Catering companies:** nLCA results could be used to inform selection of menu items based on enviro-nutritional performance. This could align with GPP policies for government customers as well, and provide competitive advantage for obtaining contracts with private sector customers.

- **Meal delivery kit companies and online food retailers:** meal-level nLCA results could be used to guide meal development by these companies and provide enviro-nutritional information about meals to customers.
- **Food-related mobile apps and websites:** nLCA results could be incorporated into online platforms, supporting more informed decision-making amongst consumers. There are already websites and apps to help consumers make nutritionally healthier food choices, for example the government-driven 'My Plate' website mentioned in section 6.4.1.2, other non-governmental/industry-driven websites (Environmental Working Group, 2025; FoodSwitch, 2025; Open Food Facts, 2025) as well as those offering a wide range of recipes to help consumers plan and cook meals at home (All Recipes, 2023; BBC Good Food, 2025; Nast, 2025). These platforms could be extended to include combined enviro-nutritional indicators based on this nLCA method.
- **Supermarkets and food service platforms:** nLCA results could be incorporated into menu planning tools and/or published recipes.

Thus nLCA-based indicators can not only support consumer decision-making but also support food companies by providing indicators to demonstrate responsible service offerings, enhance reputation and brand equity, and drive competitive advantage.

6.5 Limitations and future work

This section provides a summary of prioritised topics to address in future based on this research.

For avocado orchards, firstly, assessing terrestrial ecotoxicity impacts on agricultural soil was highlighted as an important methodological challenge in this research (Chapter 3, Section 3.5.2.4 and Chapter 6, Section 6.2.2.6). Recent advances in terrestrial ecotoxicity assessment methods allow for a more accurate approach to assign emissions to different environmental components (Nemecek et al., 2022) and this should be more widely adopted in future LCA research in agri-food. However, LCIA methods still do not model agricultural soil as part of the

ecosphere, therefore impacts of emission fractions to agricultural soil cannot be assessed. Secondly, regarding eutrophication, freshwater environments in New Zealand are often limited by both nitrogen and phosphorous; therefore there is an inherent methodological limitation when using LCIA methods based on either phosphorous or nitrogen being limited (Payen and Ledgard 2017). Therefore, in the current study, CML 2001 was used (even though ReCiPe 2016 provides more updated CFs) as it assesses emissions of both nitrogen and phosphorous to freshwater, thereby offering a 'worst-case' scenario (Chapter 3, Section 3.2.2). Future research is needed on more site-specific eutrophication CFs for the New Zealand context. Thirdly, there is no data about the environmental impacts of the nursery stage in the life cycle of the avocado orchard, and this should be addressed in future research.

For the post-harvest stages, primary data was obtained from two packhouses in the Bay of Plenty, together accounting for 27% of avocados packaged in New Zealand (Chapter 4, Section 4.3.2.1). Other packhouses may employ different operations and therefore have different environmental profiles. Moreover, both surveyed packhouses primarily process kiwifruit, with avocados forming a smaller share of their throughput, whereas some facilities specialise solely in avocados. Including data from these 'avocado-only' packhouses would likely provide additional insights. Similarly, export and domestic distribution data were sourced from AVOCO, which handles most avocado exports but only 45% of domestic distribution (Chapter 4, Section 4.3.2.2). A future study should therefore expand the **sample size** to better represent both post-harvest operations and domestic supply chains.

Another limitation relates to the **practical challenges** which arose during the course of the LCA study, the main one related to data collection. Pesticide input data was well organised and easily available via the Avogreen agrichemical diaries (growers are required to note all annual agrichemical inputs as a prerequisite for export). However, growers did not have readily available data for fertiliser, water, fuel, and electricity and had to go through annual paperwork (e.g. fuel receipts, water payments etc.) to determine the quantities used per hectare. In many

cases, it was not possible to disaggregate electricity use for the orchard and personal habitation as the orchardists' home and orchard were located on the same property and serviced by a single power line. Similarly, at the packhouse stage, packhouse personnel were unable to adequately disaggregate information regarding the different types of packaging as well as the fuel/electricity used for on-site (e.g. forklifts) and business-related transport. Suggestions for addressing these challenges in future studies include incorporating all orchard inputs (not just pesticides) into the Avogreen spray diary platform for easier and more organised access. A similar platform could be created for packhouses to enable provision of disaggregated packaging data as well.

For **nLCA** specifically, nutritional profiles of food can vary due to different production practices, climatic and geographic factors, different varieties of the same product (e.g. different salmon or mushroom species), variability in post-harvest operations, and seasonal influences (Chapter 5, Section 5.4.1.5). Further research is needed to investigate how this variability can be better represented in nLCA studies. Also, bioavailability of nutrients is an important consideration in nutritional studies, especially in the context of specific sample populations, e.g. bioavailability of iron in women of reproductive age. This aspect was not included in the nLCA study in this thesis due to lack of relevant data and should be addressed in future studies.

Another point of the nLCA study is related to the databases used in this study. For environmental impacts, the current study used the database developed by Drew et al. (2020) as it was aligned with New Zealand production and distribution conditions. However, this database was itself based on production data from Hoolohan et al. (2013), which in turn used data from as early as 2002. Therefore, a decision tree had to be used to identify values for several toppings which were more recent, based on recently published literature. A future study might look at using existing agricultural databases like ecoinvent or Agribalyse which have more recent and up-to-date production values for these toppings and then adapt the values to New Zealand conditions, for more temporal and geographic relevance. In terms of nutritional composition,

the study used data from the NZFCD and the NRV data was obtained from the combined NRV list developed for Australia and New Zealand by the National Medical Health and Research Council (2017). However, a few nutrients in the expanded NRF index had to be excluded because composition and/or NRV data was missing in the databases. For example, biotin, molybdenum, and fluoride had no composition values in the NZFCD, and chloride and sulphur had no published NRVs. Bioactive phytochemicals like flavonoids and carotenoids, and food additives were also excluded as there was no published composition or NRV data for them. This did not impact on the nLCA method reliability as the main nutrients driving the ranking differences between the chosen toppings (protein, fibre, key minerals, vitamins, and unsaturated fats) were available and included. However, including the others left out in this study might change the results for food groups where these compounds are nutritionally important. For example, Drewnowski and Burton-Freeman (2020) showed that incorporating flavonoids into nutrient profiling models recalibrates nutrient density scores for fruits, with citrus fruits and berries ranking much higher when flavonoid subclasses like flavanones, anthocyanidins, and flavan-3-ols are considered. This suggests that if meals contained such fruit-rich toppings, including flavonoids could shift rankings notably. Thus, for the current study, the choices about nutrients to include were made owing to availability of data in these particular New Zealand-specific databases; however, expanding the composition and NRV databases to include these nutrients in future, would improve the robustness of this nLCA method for more diverse meal types.

Regarding overarching themes in the research, in terms of **data quality**, more detailed data could be collected for: fertiliser origin and production processes; agrichemical active ingredients and formulation sites; truck backhauling and route specifics; fuel and refrigerant losses at the coolstore and during shipping; and the role of seasonal labour⁵².

⁵² Mithraratne et al. (2010) noted the involvement of seasonal workers in the kiwifruit sector and the associated climate change impacts involved with flying them to New Zealand for harvesting and packaging kiwifruit. Sanderson et al. (2019) re-iterate this point, stating that while transportation is not generally recognised as a hotspot in overall

The LCA study assessed five **environmental impact categories** selected during the goal and scope stage based on a materiality assessment by NZ Avocado for avocado orchards (Chapter 3, Section 3.2.2). Future LCAs should be expanded to include additional impact categories, and in particular those that are likely to be materially relevant for the post-harvest activities (e.g. acidification, stratospheric ozone depletion, and photochemical ozone formation). Also, materiality assessment for other agri-food sectors may prioritise assessment of different environmental impacts, e.g. land use change on peat soils for dairy production (Garrett, 2023; Waikato Regional Council, 2025). Similarly, the national-level nLCA study in this thesis assessed only climate change (Chapter 5, Section 5.2.2). Future applications of the nLCA framework developed in Chapter 5 should therefore broaden the scope to include additional impact categories.

All life cycle stages were not included in this research due to data unavailability. For the avocado LCA study, the nursery stage and retail and post-retailer stages in export supply chains, and post-retail distribution centre (RDC) stages in domestic distribution, were excluded and the nLCA study used a cradle-to-retail distribution RDC system boundary for climate change impacts (Chapter 4, Section 4.3.1 and Chapter 5, Section 5.2.2). Additionally, the nLCA study did not consider **changes in nutritional value along the life cycle** (Chapter 5, Section 5.2.3); the post-production nutritional value of food items may change due to transport, storage, and different food preparation methods. A future study should include these additional life cycle stages.

Uncertainty is one of the main methodological limitations of LCA (as mentioned in Chapter 1, Section 1.2.2). Uncertainty in LCA can be associated with various factors including: data

food product system impacts, it can be important and relevant in certain contexts, particularly when considering the use of foreign seasonal workers in the horticultural industry. Although the avocado sector currently does not employ many seasonal workers, industry stakeholders interviewed for this research suggested that as the supra-massive orchards come to full production, seasonal workers will need to be employed.

parameters (inaccuracy, gaps, non-representative), model uncertainty, value-based choices (like allocation rules, functional unit, and system boundaries), spatial and temporal variability, epistemological uncertainty (lack of knowledge about processes), and researcher mistakes (Björklund, 2002; Heijungs & Huijbregts, 2004; Huijbregts, 1998; Pelletier, 2017). In this study, uncertainty was addressed through the use of data ranges, sensitivity analyses, and scenario comparisons. Future research could further address uncertainty by using mathematical approaches like Monte Carlo simulations.

Since addressing all **three dimensions of sustainability** was beyond the scope of this thesis, future research could address the social and economic dimensions more comprehensively. For example, Life Cycle Sustainability Assessment (LCSA) could be used (Matos et al., 2024; Onat et al., 2017).

As part of a broader study, it should be noted that nLCA studies do not address the broader **food environment**⁵³ which strongly shapes actual consumption patterns. Indeed, relative affordability often outweighs nutritional quality or environmental sustainability in shaping consumer choices (Headey & Alderman, 2019). Future research could incorporate affordability alongside nLCA-based assessments to provide a more holistic understanding of sustainable food consumption (Batlle-Bayer et al., 2020; Drewnowski et al., 2021).

This research focused on **conventional production systems**, as they dominate global food production and most New Zealand avocado growers use conventional cultivation techniques. Organic agriculture accounts for just over 2% of global agricultural land, while biodynamic and other regenerative systems occupy even smaller areas (Schlatter et al., 2025). However, alternative production systems are becoming more popular; for example, organically cultivated

⁵³ The food environment encompasses the physical, economic, socio-cultural, and policy conditions that determine access, affordability, safety, and preferences (HLPE, 2020), all of which influence what people eat (Clune, 2019; Downs et al., 2020).

land globally grew from 10 million hectares in 1998 to nearly 99 million hectares in 2025 (Brito et al., 2022; Cucurachi et al., 2019; Schlatter et al., 2025). Current VSS for organic or biodynamic production remain largely practice-based and lack performance-oriented metrics. Future research could therefore explore developing LCA-based indicators for these alternative systems to complement existing practice-based standards.

Lastly, LCA is inherently context-specific, as results depend on geographically and temporally bounded data, production practices, background energy systems, and consumption patterns. Accordingly, the LCA and nLCA results presented in this study are intended to be interpreted within the New Zealand context, reflecting New Zealand-specific production systems, supply chains, dietary habits, and reference data. Direct transfer of these results to other national contexts without adjustment would be inappropriate.

6.6 Final conclusion

Environmental LCA is a useful systemic tool to operationalise sustainability along the life cycle of agri-food systems and is recognised as an important tool to support progress towards both SCP and SFS. This thesis addresses the research aim: ‘to identify how LCA-based approaches can support more sustainable agri-food production and consumption in New Zealand’ This aim has been achieved by: 1) providing recommendations about use of LCA in developing indicators for agri-food VSS; and 2) developing an nLCA method that combines environmental and nutritional information at the meal level. With respect to sustainable production, the main focus was a case study of the New Zealand avocado sector, however, the insights from the research can be applied more widely in other agri-food sectors as discussed in Sections 6.2.2. With respect to sustainable consumption the nLCA methodology developed in this research can also be refined and adapted for applicability to New Zealand, as discussed in Section 6.3.2.

In addition, this thesis also contributes to the academic literature as little attention has been given to the use of LCA in agri-food VSS; the limited literature that exists focuses overwhelmingly on the carbon footprint tools used in some VSS. Moreover, nLCA is a relatively

new but growing area of study, with relatively sparse attention given to meal-level assessments. This thesis addresses both these research gaps and therefore contributes to supporting more sustainable agri-food production and consumption in New Zealand.

References

- Alaphilippe, A., Boissy, J., Simon, S., & Godard, C. (2016). Environmental impact of intensive versus semi-extensive apple orchards: Use of a specific methodological framework for Life Cycle Assessments (LCA) in perennial crops. *Journal of Cleaner Production*, 127, 555–561. <https://doi.org/10.1016/j.jclepro.2016.04.031>
- All Recipes. (2023). *About Us*. Allrecipes. <https://www.allrecipes.com/about-us-6648102> (Accessed 13 November 2023)
- Astier, M., Merlín-Uribe, Y., Villamil-Echeverri, L., Garcíarreal, A., Gavito, M. E., & Masera, O. R. (2014). Energy balance and greenhouse gas emissions in organic and conventional avocado orchards in Mexico. *Ecological Indicators*, 43, 281–287. <https://doi.org/10.1016/j.ecolind.2014.03.002>
- Audsley, E. (1997). *Harmonisation of environmental Life Cycle Assessment for agriculture*. European Commission DG VI Agriculture (1997).
- Barizon, R. R. M. (2021). *PestLCI Model: Parameterization for scenarios of Brazilian agricultural production*. Documentos 132, ISSN 1516-4691. <https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1137347>
- Barry, M. T. (2011). *Life Cycle Assessment and the New Zealand Wine Industry: A tool to support continuous environmental improvement*. [Master's thesis, Massey University, Wellington, New Zealand]. Massey Research Online. <https://mro.massey.ac.nz/items/95e2dc84-1144-4e0b-9661-04c093141bf9>
- Batlle-Bayer, L., Bala, A., Albertí, J., Xifré, R., Aldaco, R., & Fullana-i-Palmer, P. (2020). Food affordability and nutritional values within the functional unit of a food LCA. An application on regional diets in Spain. *Resources, Conservation and Recycling*, 160, 104856. <https://doi.org/10.1016/j.resconrec.2020.104856>
- BBC Good Food. (2025). *Family Meal Recipes*. <https://www.bbcgoodfood.com/recipes/collection/family-meal-recipes> (Accessed 10 August 2025)
- Berardy, A., Johnston, C. S., Plukis, A., Vizcaino, M., & Wharton, C. (2019). Integrating Protein Quality and Quantity with Environmental Impacts in Life Cycle Assessment. *Sustainability*, 11(10), Article 10. <https://doi.org/10.3390/su11102747>

- Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U., & Hallström, E. (2020). Systematic Evaluation of Nutrition Indicators for Use within Food LCA Studies. *Sustainability*, 12(21), Article 21. <https://doi.org/10.3390/su12218992>
- Bioeconomy Science Institute. (2021). *Reliable and up-to-date nutrient data for New Zealand foods · Plant & Food Research*. Plant & Food Research. <https://www.plantandfood.com/en-nz/article/reliable-and-up-to-date-and-nutrient-data-for-new-zealand-foods/> (Accessed 10 August 2025)
- Birkved, M., & Hauschild, M. Z. (2006). PestLCI—A model for estimating field emissions of pesticides in agricultural LCA. *Ecological Modelling*, 198(3–4), 433–451. <https://doi.org/10.1016/j.ecolmodel.2006.05.035>
- Björklund, A. E. (2002). Survey of approaches to improve reliability in LCA. *The International Journal of Life Cycle Assessment*, 7(2), 64–72. <https://doi.org/10.1007/BF02978849>
- Bojacá, C. R., Wyckhuys, K. A. G., & Schrevels, E. (2014). Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. *Journal of Cleaner Production*, 69, 26–33. <https://doi.org/10.1016/j.jclepro.2014.01.078>
- Bonsucro. (2025). *Bonsucro Outcome report 2023-24*. <https://bonsucro.com/wp-content/uploads/Bonsucro-Outcome-Report-2023-24.pdf>
- Bord Bia. (2021). *Origin Green progress report 2021*. <https://www.origingreen.ie/globalassets/origingreen/bord-bia-origin-green-progress-update-report-2021.pdf>
- Bord Bia. (2023). *Origin Green Progress Update Report 2023*. <https://www.origingreen.ie/globalassets/bb-progress-report-2023-002.pdf>
- Boschiero, M., Zanotelli, D., Ciarapica, F. E., Fadanelli, L., & Tagliavini, M. (2019). Greenhouse gas emissions and energy consumption during the post-harvest life of apples as affected by storage type, packaging and transport. *Journal of Cleaner Production* 220, 45-56. <https://doi.org/10.1016/j.jclepro.2019.01.300>.
- Boulay, A. M., & Lenoir, L. (2020). Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations. *Ecological Indicators*, 111, 106017. <https://doi.org/10.1016/j.ecolind.2019.106017>
- BREEAM. (2025). *A guide to how BREEAM works*. BREEAM. <https://breeam.com/about/how-breeam-works> (Accessed 10 August 2025)

- Brito, T. P., de Souza-Esquerdo, V. F., & Borsatto, R. S. (2022). State of the art on research about organic certification: A systematic literature review. *Organic Agriculture*, 12(2), 177–190. <https://doi.org/10.1007/s13165-022-00390-6>
- Bush, S. R., & Oosterveer, P. (2015). Vertically Differentiating Environmental Standards: The Case of the Marine Stewardship Council. *Sustainability*, 7(2), Article 2. <https://doi.org/10.3390/su7021861>
- Canterbury Regional Council. (2024). *Farm Environment Plans*. Environment Canterbury. <https://www.ecan.govt.nz/your-region/farmers-hub/farming-plans-and-consenting/farm-environment-plans> (Accessed 10 August 2025)
- Cerutti, A. K., Beccaro, G. L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., & Bounous, G. (2014). Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. *Journal of Cleaner Production*, 73, 125–135. <https://doi.org/10.1016/j.jclepro.2013.09.017>
- Cerutti, A. K., Bruun, S., Beccaro, G. L., & Bounous, G. (2011). A review of studies applying environmental impact assessment methods on fruit production systems. *Journal of Environmental Management*, 92(10), 2277–2286. <https://doi.org/10.1016/j.jenvman.2011.04.018>
- Chobtang, J. (2016). *Appraisal of the environmental sustainability of milk production systems in New Zealand*. [Doctoral dissertation, Massey University, New Zealand]. Massey Research Online. <https://mro.massey.ac.nz/items/dd7b3215-7e5e-4fd3-a53e-d8fdc44402e0>
- Clark, M., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences*, 116(46), 23357–23362. <https://doi.org/10.1073/pnas.1906908116>
- Clark, M., Springmann, M., Rayner, M., Scarborough, P., Hill, J., Tilman, D., Macdiarmid, J. I., Fanzo, J., Bandy, L., & Harrington, R. A. (2022). Estimating the environmental impacts of 57,000 food products. *Proceedings of the National Academy of Sciences*, 119(33), e2120584119. <https://doi.org/10.1073/pnas.2120584119>
- Clune, S. (2019). Calculating GHG impacts of meals and menus using streamlined LCA data. In *Environmental Nutrition* (pp. 157–178). Elsevier. <https://doi.org/10.1016/B978-0-12-811660-9.00010-2>

- Costantini, M., Ferrante, V., Guarino, M., & Bacenetti, J. (2021). Environmental sustainability assessment of poultry productions through life cycle approaches: A critical review. *Trends in Food Science & Technology* 110, 210-212. <https://doi.org/10.1016/j.tifs.2021.01.086>
- Cossu, D., Zanchi, L., Maranghi, S., Zamagni, A., Gaias, G., Duce, P., & Vagnoni, E. (2023). Ecolabelling for improving sustainability of agri-food supply chain: An experimental implementation of the made green in Italy scheme on the hard sheep milk cheese. *Cleaner Environmental Systems*, 100153. <https://doi.org/10.1016/j.cesys.2023.100153>
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), Article 3. <https://doi.org/10.1038/s43016-021-00225-9>
- Cucurachi, S., Scherer, L., Guinée, J., & Tukker, A. (2019). Life Cycle Assessment of Food Systems. *One Earth*, 1(3), 292–297. <https://doi.org/10.1016/j.oneear.2019.10.014>
- Deconinck, K., & Hobeika, M. (2023). *Understanding the impact of consumer-oriented assurance schemes: A review of voluntary standards and labels for the environmental sustainability of agri-food products*. OECD. Available for download at: https://www.oecd.org/en/publications/understanding-the-impact-of-consumer-oriented-assurance-schemes_af917674-en.html
- Dijkman, T. J., Birkved, M., & Hauschild, M. Z. (2012). PestLCI 2.0: A second generation model for estimating emissions of pesticides from arable land in LCA. *The International Journal of Life Cycle Assessment*, 17(8), 973–986. <https://doi.org/10.1007/s11367-012-0439-2>
- Downs, S. M., Ahmed, S., Fanzo, J., & Herforth, A. (2020). Food Environment Typology: Advancing an Expanded Definition, Framework, and Methodological Approach for Improved Characterization of Wild, Cultivated, and Built Food Environments toward Sustainable Diets. *Foods*, 9(4), 532. <https://doi.org/10.3390/foods9040532>
- Drewnowski, A. (2005). Concept of a nutritious food: Toward a nutrient density score. *The American Journal of Clinical Nutrition*, 82(4), 721–732. <https://doi.org/10.1093/ajcn/82.4.721>
- Drewnowski, A. (2017). Uses of nutrient profiling to address public health needs: From regulation to reformulation. *Proceedings of the Nutrition Society*, 76(3), 220–229. <https://doi.org/10.1017/S0029665117000416>

- Drewnowski, A., and Burton-Freeman, B. (2020). A new category-specific nutrient rich food (NRF9f.3) score adds flavonoids to assess nutrient density of fruit. *Food and Function*, 11, 123-130. [https://doi.org/ 10.1039/c9fo02344e](https://doi.org/10.1039/c9fo02344e)
- Drewnowski, A., Amanquah, D., & Gavin-Smith, B. (2021). Perspective: How to Develop Nutrient Profiling Models Intended for Global Use: A Manual. *Advances in Nutrition*, 12(3), 609–620. <https://doi.org/10.1093/advances/nmab018>
- Environmental Working Group. (2025). *What's Really in Your Food?* <https://www.ewg.org/foodscores/> (Accessed 9 August 2025)
- EPD International. (2019). *PCR Fruits and nuts. Product Category Classification UN CPC 013. 2019-01, Version 1.01. Valid until 21/01/2023.* (Version 1.01) [UN CPC 013]. Available for download at: <https://api.environdec.com/api/v1/EPDLibrary/Files/40cecf40-cb08-4a86-174e-08dc25c78130/Data>
- European Union. (2020). *Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System.* https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf
- Fantke, P. (2019). Modelling the environmental impacts of pesticides in agriculture. In B. P. Weidema (Ed.), *Assessing the environmental impact of agriculture* (pp. 177–228). Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2018.0044.08>
- FAO. (2021). *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point (SOLAW 2021).* FAO. <https://doi.org/10.4060/cb7654en>
- FAO & WHO. (2019). *Sustainable healthy diets—Guiding principles.* Available for download at: <https://www.who.int/publications/i/item/9789241516648>
- Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A., & Drewnowski, A. (2015). The Nutrient Balance Concept: A New Quality Metric for Composite Meals and Diets. *PLOS ONE*, 10(7), e0130491. <https://doi.org/10.1371/journal.pone.0130491>
- Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of The Total Environment*, 805, 150106. <https://doi.org/10.1016/j.scitotenv.2021.150106>
- Fonterra. (2024). *Suppliers of Warehouse and Distribution Services: Fonterra Food Safety and Quality Requirements.* <https://www.fonterra.com/content/dam/fonterra-public->

website/fonterra-new-zealand/documents/pdf/food-quality-and-safety/FSQ-requirements-for-suppliers-of-warehousing-and-distribution-services.pdf

Fonterra. (2025). *Sustainability*. Fonterra. <https://www.fonterra.com/nz/en/sustainability.html> (Accessed 15 August 2025)

Fulgoni, V. L., III, Keast, D. R., & Drewnowski, A. (2009). Development and Validation of the Nutrient-Rich Foods Index: A Tool to Measure Nutritional Quality of Foods. *The Journal of Nutrition*, 139(8), 1549–1554. <https://doi.org/10.3945/jn.108.101360>

FoodSwitch. (2025). *FoodSwitch -Transforming food for a healthier future*. <https://www.foodswitch.com/> (Accessed 14 August 2025)

Galindro, B. M., Zanghelini, G. M., & Soares, S. R. (2019). Use of benchmarking techniques to improve communication in life cycle assessment: A general review. *Journal of Cleaner Production*, 213, 143–157. <https://doi.org/10.1016/j.jclepro.2018.12.147>

Galloway, C., Swanepoel, P. A., & Haarhoff, S. J. (2024). A carbon footprint assessment for pasture-based dairy farming systems in South Africa. *Frontiers in Sustainable Food Systems*, 8. <https://doi.org/10.3389/fsufs.2024.1333981>

Garrett, L. (2023). *Potential for paludiculture in New Zealand*. https://niwa.co.nz/sites/default/files/inline-images/FINAL_Paludiculture_Potential_NZ_V2_220523_0.pdf

Gasso, V., Barber, A., Moller, H., Bayonne, E., Oudshoorn, F. W., & Sørensen, C. G. (2025). Benchmarking for locally tuned sustainability: The case of energy and water use in New Zealand vineyards. *Environmental and Sustainability Indicators*, 25, 100536. <https://doi.org/10.1016/j.indic.2024.100536>

Gisborne District Council. (2021). *Farm environment plans*. Gisborne District Council. <https://www.gdc.govt.nz/environment/farming/farm-environment-plans> (Accessed 14 August 2025)

Global Panel on Agriculture and Food Systems for Nutrition. (2020). *Foresight 2.0. Future food systems: For people, planet, and prosperity*. Available for download at: <https://foresight.glopan.org/>

González-García, S., Gomez-Fernández, Z., Dias, A. C., Feijoo, G., Moreira, M. T., & Arroja, L. (2014). Life Cycle Assessment of broiler chicken production: a Portuguese case study. *Journal of Cleaner Production* 74, 125-134. <http://dx.doi.org/10.1016/j.jclepro.2014.03.067>

- Graefe, S., Tapasco, J., & Gonzalez, A. (2013). Resource use and GHG emissions of eight tropical fruit species cultivated in Colombia. *Fruits*, 68(4), 303–314.
<https://doi.org/10.1051/fruits/2013075>
- Greater Wellington Regional Council. (2025). *A farmer's guide to Farm Plans in the Wellington Region*. Greater Wellington. <https://www.gw.govt.nz/environment/land-use/farm-plans/> (Accessed 14 August 2025)
- Green, A., Nemecek, T., Chaudhary, A., & Mathys, A. (2020). Assessing nutritional, health, and environmental sustainability dimensions of agri-food production. *Global Food Security*, 26, 100406. <https://doi.org/10.1016/j.gfs.2020.100406>
- Green, A., Nemecek, T., & Mathys, A. (2023). A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: The metrics and their assumptions matter. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02210-9>
- Green, A., Nemecek, T., Smetana, S., & Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696.
<https://doi.org/10.1016/j.jclepro.2021.127696>
- Grigoriadis, V., Nugent, A., & Brereton, P. (2021). Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends in Food Science & Technology*, 112, 298–311. <https://doi.org/10.1016/j.tifs.2021.03.047>
- Hallström, E., Davis, J., Woodhouse, A., & Sonesson, U. (2018). Using dietary quality scores to assess sustainability of food products and human diets: A systematic review. *Ecological Indicators*, 93, 219–230. <https://doi.org/10.1016/j.ecolind.2018.04.071>
- Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., & Ziegler, F. (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production*, 230, 402–411. <https://doi.org/10.1016/j.jclepro.2019.04.229>
- Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-56475-3>
- Headey, D. D., & Alderman, H. H. (2019). The Relative Caloric Prices of Healthy and Unhealthy Foods Differ Systematically across Income Levels and Continents. *The Journal of Nutrition*, 149(11), 2020–2033. <https://doi.org/10.1093/jn/nxz158>

- Heijungs, R., & Huijbregts, M. A. J. (2004). *A Review of Approaches to Treat Uncertainty in LCA*. Available for download at: <https://scholarsarchive.byu.edu/iemssconference/2004/all/197/>
- Herath, I., Green, S., Horne, D., Singh, R., McLaren, S., & Clothier, B. (2013). Water footprinting of agricultural products: Evaluation of different protocols using a case study of New Zealand wine. *Journal of Cleaner Production*, 44, 159–167. <https://doi.org/10.1016/j.jclepro.2013.01.008>
- Herath, I., Green, S., Singh, R., Horne, D., Van Der Zijpp, S., & Clothier, B. (2013). Water footprinting of agricultural products: A hydrological assessment for the water footprint of New Zealand's wines. *Journal of Cleaner Production*, 41, 232–243. <https://doi.org/10.1016/j.jclepro.2012.10.024>
- Higham, C. D., Singh, R., & Horne, D. J. (2024). The Water Footprint of Pastoral Dairy Farming: The Effect of Water Footprint Methods, Data Sources and Spatial Scale. *Water*, 16(3), 391. <https://doi.org/10.3390/w16030391>
- HLPE. (2020). *Food security and nutrition: Building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*. <https://www.fao.org/3/ca9731en/ca9731en.pdf>
- Huijbregts, M. A. J. (1998). Application of uncertainty and variability in LCA. *The International Journal of Life Cycle Assessment*, 3(5), 273–280. <https://doi.org/10.1007/BF02979835>
- Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & Van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, 22(2), 138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- James-Martin, G., Baird, D. L., Hendrie, G. A., Bogard, J., Anastasiou, K., Brooker, P. G., Wiggins, B., Williams, G., Herrero, M., Lawrence, M., Lee, A. J., & Riley, M. D. (2022). Environmental sustainability in national food-based dietary guidelines: A global review. *The Lancet Planetary Health*, 6(12), e977–e986. [https://doi.org/10.1016/S2542-5196\(22\)00246-7](https://doi.org/10.1016/S2542-5196(22)00246-7)
- Kyttä, V., Kårlund, A., Pellinen, T., Pietiläinen, O., Tuomisto, H. L., Kolehmainen, M., Pajari, A.M., & Saarinen, M. (2023). Product-group-specific nutrient index as a nutritional functional unit for the Life Cycle Assessment of protein-rich foods. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02217-2>

- Lam, W. Y., Sim, S., Kulak, M., Van Zelm, R., Schipper, A. M., & Huijbregts, M. A. J. (2021). Drivers of variability in greenhouse gas footprints of crop production. *Journal of Cleaner Production*, 315, 128121. <https://doi.org/10.1016/j.jclepro.2021.128121>
- Ledgard, S. F., Falconer, S. J., Abercrombie, R., Philip, G., & Hill, J. P. (2020). Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. *Journal of Dairy Science*, 103(1), 1031–1046. <https://doi.org/10.3168/jds.2019-17182>
- Ledgard, S., Falconer, S., & Mazzetto, A. (2021). *Carbon footprint of New Zealand beef and sheep exported to different markets*.
https://beeflambnz.com/sites/default/files/levies/files/BLNZ_review_report.pdf
- Lees, D. N. (2020). *The Irish Origin Green Sustainability Brand An Evaluation of the Relevance for New Zealand*. Available for download at:
<https://researcharchive.lincoln.ac.nz/entities/publication/5aa2f4e9-fe59-4b76-b016-ad536d200a2d>
- Leinonen, I., & Kyriazakis, I. (2016). How can we improve the environmental sustainability of poultry production? *The Proceedings of the Nutrition Society* 75(3), 265-273.
<https://doi.org/10.1017/S0029665116000094>
- Livingstone, M. B. E., & Pourshahidi, L. K. (2014). Portion size and obesity. *Advances in Nutrition (Bethesda, Md.)*, 5(6), 829–834. <https://doi.org/10.3945/an.114.007104>
- Lupo, C., Clay, D. E., Benning, J. L., & Stone, J. J. (2013). Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA. *Journal of Environmental Quality*, 42(5), 1386–1394. <https://doi.org/10.2136/sssaj1990.03615995005400010042x>
- Mackay, S., Gerritsen, S., Sing, F., Vandevijvere, S., & Swinburn, B. (2022). Implementing healthy food environment policies in New Zealand: Nine years of inaction. *Health Research Policy and Systems*, 20(1), 8. <https://doi.org/10.1186/s12961-021-00809-8>
- Martínez-Blanco, J., Antón, A., Rieradevall, J., Castellari, M., & Muñoz, P. (2011). Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization. *The International Journal of Life Cycle Assessment*, 16(1), 12–26. <https://doi.org/10.1007/s11367-010-0238-6>
- Matos, C., Junkes, V. H., Lermen, F. H., Magalhães, R. F. de, Matias, G. de S., Ribeiro, J. L. D., Lenzi, G. G., & Siqueira, H. V. (2024). Life cycle sustainability assessment of the agri-food chain: Empirical review and bibliometrics. *Production*, 34.
<https://www.redalyc.org/journal/3967/396776753003/html/>

- Matse, D. T., Geretharan, T., Van Gorp, E. F., Anderson, S., Jeyakumar, P., & Anderson, C. W. N. (2024). The Potential Impact of Long-Term Copper Fungicide Sprays on Soil Health in Avocado Orchards. *Environments*, 11(6), 109.
<https://doi.org/10.3390/environments11060109>
- Mazac, R., Järviö, N., & Tuomisto, H. L. (2023). Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. *Science of The Total Environment*, 876, 162796. <https://doi.org/10.1016/j.scitotenv.2023.162796>
- Mazzetto, A., Falconer, S., & Ledgard, S. (2021). *Updating the carbon footprint for selected New Zealand agricultural products an update for milk*. Report for the Ministry for Primary Industries (MPI) RE450/2021/055. <https://www.mpi.govt.nz/dmsdocument/51076-Updating-the-carbon-footprint-for-selected-New-Zealand-agricultural-products-an-update-for-milk/>
- MBIE. (n.d.). *Submission on Te Ara Paerangi Future Pathways green paper*. Available for download at: <https://www.mbie.govt.nz/have-your-say/future-pathways>
- McAuliffe, G. A., Takahashi, T., & Lee, M. R. F. (2018). Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. *Food and Energy Security*, 7(3), e00143. <https://doi.org/10.1002/fes3.143>
- McGeough, E. J., Little, S. M., Janzen, H. H., McAllister, T. A., McGinn, S. M., & Beauchemin, K. A. (2012). Life-cycle assessment of greenhouse gas emissions from dairy production in Eastern Canada: A case study. *Journal of Dairy Science*, 95(9), 5164–5175.
<https://doi.org/10.3168/jds.2011-5229>
- McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., De Camillis, C., Renouf, M., Rugani, B., Saarinen, M., van der Pols, J., Vázquez-Rowe, I., Vallejo, A. A., Bianchi, M., Chaudhary, A., Chen, C., Cooreman-Algoed, M., Dong, H., Grant, T., ... van Zanten, H. (2021a). *Integration of environment and nutrition in life cycle assessment of food Items: Opportunities and challenges*. <https://doi.org/10.4060/cb8054en>
- McLaren, S., Clothier, B., Barber, A., McNally, S., Bullen, L., Mazzetto, A., & Ledgard, S. (2021b). *Updating the carbon footprints for selected New Zealand agricultural products*. <https://www.mpi.govt.nz/dmsdocument/51079-Updating-the-carbon-footprint-for-selected-New-Zealand-agricultural-products-an-update-for-apples-kiwifruit-and-wine/>
- Mekonnen, M. M., & Hoekstra, A. Y. (2014). Water footprint benchmarks for crop production: A first global assessment. *Ecological Indicators*, 46, 214–223.
<https://doi.org/10.1016/j.ecolind.2014.06.013>

- Merrington, G., Rogers, S. L., & Zwieten, L. V. (2002). The potential impact of long-term copper fungicide usage on soil microbial biomass and microbial activity in an avocado orchard. *Soil Research*, 40(5), 749–759. <https://doi.org/10.1071/sr01084>
- MfE. (2021). *Climate Change Response (Zero Carbon) Amendment Act 2019*. Ministry for the Environment. <https://environment.govt.nz/acts-and-regulations/acts/climate-change-response-amendment-act-2019/> (Accessed 15 August 2025)
- MfE. (2023). *Agriculture emissions and climate change*. Ministry for the Environment. <https://environment.govt.nz/facts-and-science/climate-change/agriculture-emissions-climate-change/> (Accessed 24 October 2024)
- Milà I Canals, L., Burnip, G. M., & Cowell, S. J. (2006). Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. *Agriculture, Ecosystems & Environment*, 114(2–4), 226–238. <https://doi.org/10.1016/j.agee.2005.10.023>
- Ministry of Education. (2025a). *External Supplier Sustainability KPI: Waste to Landfill Term 2 & 3 2024*. <https://kaorakaako.education.govt.nz/working-together/waste-minimisation/external-supplier-sustainability-kpi-s> (Accessed 16 August 2025)
- Ministry of Education. (2025b). *Ka Ora, Ka Ako | Healthy School Lunches: About the programme*. <https://www.education.govt.nz/education-professionals/schools-year-0-13/healthy-school-lunches/ka-ora-ka-ako-healthy-school-lunches-about-programme> (Accessed 16 August 2025)
- Ministry of Health. (2020). *Eating and Activity Guidelines for New Zealand Adults—2020*. Available for download at: <https://www.tewhatuora.govt.nz/health-services-and-programmes/nutrition/eating-and-activity-guidelines>
- Mithraratne, N., Barber, A., & McLaren, S. J. (2010). *Carbon footprinting of the kiwifruit supply chain—Report on methodology and scoping study*. https://www.landcareresearch.co.nz/assets/researchpubs/Kiwifruit_Methodology_Report_2010.pdf
- Mozaffarian, D., Micha, R., & Wallace, S. (2010). Effects on Coronary Heart Disease of Increasing Polyunsaturated Fat in Place of Saturated Fat: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *PLOS Medicine*, 7(3), e1000252. <https://doi.org/10.1371/journal.pmed.1000252>

- MPI. (2023). *The future of Aotearoa New Zealand's food sector: Exploring demand opportunities in the year 2050*. <https://www.mpi.govt.nz/dmsdocument/56350-The-Future-of-Aotearoa-New-Zealands-Food-Sector-Exploring-Global-Demand-Opportunities-in-the-Year-2050/>
- MPI. (2025, June 10). *About the Primary Sector Growth Fund | NZ Government*. About the Primary Sector Growth Fund. <https://www.mpi.govt.nz/funding-rural-support/primary-sector-growth-fund/about-the-primary-sector-growth-fund/> (Accessed 17 August 2025)
- Nast, C. (2025). *Epicurious – Recipes, Menu Ideas, Videos & Cooking Tips*. Epicurious. <https://www.epicurious.com/> (Accessed 17 August 2025)
- National Medical Health and Research Council. (2017). *Nutrient Reference Values (NRVs) for Australia and New Zealand Including Recommended Dietary Intakes*. Available for download at: <https://www.nhmrc.gov.au/about-us/publications/nutrient-reference-values-australia-and-new-zealand-including-recommended-dietary-intakes-block-views-block-file-attachments-content-block-1>
- Nemecek, T., Antón, A., Basset-Mens, C., Gentil-Sergent, C., Renaud-Gentié, C., Melero, C., Naviaux, P., Peña, N., Roux, P., & Fantke, P. (2022). Operationalising emission and toxicity modelling of pesticides in LCA: The OLCA-Pest project contribution. *The International Journal of Life Cycle Assessment*, 27(4), 527–542. <https://doi.org/10.1007/s11367-022-02048-7>
- Nemecek, T., Bengoa, X., Lansche, J., Roesch, A., Faist-Emmenegger, M., Rossi, V., & Humbert, S. (2020). *Methodological Guidelines for the Life Cycle Inventory of Agricultural Products—World Food LCA Database*. https://simapro.com/wp-content/uploads/2020/11/WFLDB_MethodologicalGuidelines_v3.5.pdf
- Nemecek, T., Roesch, A., Bystricky, M., Jeanneret, P., Lansche, J., Stüssi, M., & Gaillard, G. (2023). Swiss Agricultural Life Cycle Assessment: A method to assess the emissions and environmental impacts of agricultural systems and products. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02255-w>
- Nemecek, T., & Schnetzer, J. (2012). *Methods of assessment of direct field emissions for LCIs of agricultural production systems*. Agroscope Reckenholz-Tänikon Research Station ART & ecoinvent Centre. Available for download at: www.ecoinvent.org
- Newton, R. W., & Little, D. C. (2018). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. *The International Journal of Life Cycle Assessment* 23(5), 1018-1029. <https://doi.org/10.1007/s11367-017-1386-8>

- New Zealand Food Composition Database (NZFCD). (2022). *Search for a Food—New Zealand Food Composition Database*. <https://www.foodcomposition.co.nz/search/food> (Accessed 26 October 2023)
- New Zealand Government Procurement. (2025). *Implementing broader outcomes*. New Zealand Government Procurement. <https://www.procurement.govt.nz/guides/broader-outcomes/implementing-broader-outcomes/> (Accessed 14 August 2025)
- Nicese, F. P., & Lazzerini, G. (2012). CO₂ sources and sinks in ornamental plant nurseries. *International Society for Horticultural Science*.
http://www.actahort.org/books/990/990_8.htm
- North Dakota State University. (2025). *Backgrounding Cattle | NDSU Agriculture*.
<https://www.ndsu.edu/agriculture/ag-hub/ag-topics/livestock/beef/production/backgrounding-cattle> (Accessed 11 August 2025)
- Notarnicola, B., Salomone, R., Petti, L., Renzulli, P. A., Roma, R., & Cerutti, A. K. (Eds.). (2015). *Life Cycle Assessment in the Agri-food Sector: Case Studies, Methodological Issues and Best Practices*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-11940-3>
- Notarnicola, B., Sala, S., Anton, A., McLaren, S. J., Saouter, E., & Sonesson, U. (2017). The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, 140, 399–409.
<https://doi.org/10.1016/j.jclepro.2016.06.071>
- NZ Apples and Pears. (2024). *Journey Through a Season—Packed Fruit*.
<https://www.applesandpears.nz/our-apples-pears/journey-through-a-season/> (Accessed 13 August 2025)
- NZ Wine. (2020). *NZ Wine sustainability overview*.
<https://www.nzwine.com/media/16274/nzw-sustainability-overview.pdf>
- OECD. (2022). *Improving environmental outcomes along food supply chains: A review of initiatives and their effectiveness* (OECD Food, Agriculture and Fisheries Papers 186; OECD Food, Agriculture and Fisheries Papers, Vol. 186). <https://doi.org/10.1787/d549eb43-en>
- Onat, N., Kucukvar, M., Halog, A., & Cloutier, S. (2017). Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives. *Sustainability*, 9(5), 706. <https://doi.org/10.3390/su9050706>

- Oonincx, D., & de Boer, I. (2012). Environmental impact of the production of mealworms as a protein source for humans—A life cycle assessment. *PLoS ONE*, 7(12), e51145–e51145. <https://doi.org/10.1371/journal.pone.0051145>
- Open Food Facts. (2025). *Open Food Facts – Discover*. <https://world.openfoodfacts.org/> (Accessed 16 August 2025)
- Palliser, C. C., Rutherford, J. C., & MacCormick, A. (2019). Eutrophication in Lake Rotorua. 1. Using OVERSEER to estimate historic nitrogen loads. *New Zealand Journal of Agricultural Research*, 62(1), 112–129. <https://doi.org/10.1080/00288233.2018.1488748>
- Payen, S., & Ledgard, S. F. (2017). Aquatic eutrophication indicators in LCA: Methodological challenges illustrated using a case study in New Zealand. *Journal of Cleaner Production*, 168, 1463–1472. <https://doi.org/10.1016/j.jclepro.2017.09.064>
- Pelletier, N., Ibarburu, M., & Xin, H. (2013). A carbon footprint analysis of egg production and processing supply chains in the Midwestern United States. *Journal of Cleaner Production* 54, 108–114. <https://doi.org/10.1016/j.jclepro.2013.04.041>
- Pelletier, N. (2017). Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. *Journal of Cleaner Production*, 152, 167–180. <https://doi.org/10.1016/j.jclepro.2017.03.050>
- Picoli, J. F., Barizon, R. R. M., Birkved, M., & Folegatti-Matsuura, M. I. S. (2018). Modelling of pesticide emissions for life cycle assessment of agricultural products. Available for download at: <https://www.alice.cnptia.embrapa.br/alice/handle/doc/1103479>
- Poore, J., & Nemecek, T. (2018). Reducing food’s environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. Scopus®. <https://doi.org/10.1126/science.aaq0216>
- Putman, B., Rotz, C. A., & Thoma, G. (2023). A comprehensive environmental assessment of beef production and consumption in the United States. *Journal of Cleaner Production*, 402, 136766. <https://doi.org/10.1016/j.jclepro.2023.136766>
- Ravaut, G., Légiot, A., Bergeron, K.-F., & Mounier, C. (2021). Monounsaturated Fatty Acids in Obesity-Related Inflammation. *International Journal of Molecular Sciences*, 22(1), Article 1. <https://doi.org/10.3390/ijms22010330>
- Real Estate Authority. (2020). *Rural environmental issues (CPD training resource, v1.0F)*. https://www.rea.govt.nz/assets/Uploads/Resources/REA-CPD-Rural_environmental-issues_v1.0F.pdf

- Renaud-Gentié, C., Dijkman, T. J., Bjorn, A., & Birkved, M. (2014). *Modeling pesticides emissions for Grapevine Life Cycle Assessment: Adaptation of Pest-LCI model to viticulture*.
https://backend.orbit.dtu.dk/ws/portalfiles/portal/101753699/Modeling_pesticides_emissions.pdf
- Robertson, N. (2023). *Single Point of Entry for kiwifruit exporting: Impacts on the New Zealand kiwifruit industry*. <https://canopy.zespri.com/content/dam/new-canopy/nz/en/documents/public/news/2023-NZKGI-Report-on-Single-Desk.pdf>
- Rosenbaum, R. K., Anton, A., Bengoa, X., Bjørn, A., Brain, R., Bulle, C., Cosme, N., Dijkman, T. J., Fantke, P., Felix, M., Geoghegan, T. S., Gottesbüren, B., Hammer, C., Humbert, S., Jolliet, O., Juraske, R., Lewis, F., Maxime, D., Nemecek, T., ... Wallman, M. (2015). The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA. *The International Journal of Life Cycle Assessment*, 20(6), 765–776.
<https://doi.org/10.1007/s11367-015-0871-1>
- Saarinen, M., Fogelholm, M., Tahvonen, R., & Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, 149, 828–844. <https://doi.org/10.1016/j.jclepro.2017.02.062>
- Sachs, J. D., Lafortune, G., Fuller, G., & Iablonski, G. (2025). *Sustainable Development Report 2025. Financing Sustainable Development to 2030 and Mid-Century*. Dublin University Press.
<https://doi.org/10.25546/111909>
- Sameshima, H., Akamatsu, R., Hayashi, F., & Takemi, Y. (2023). Estimation of greenhouse gas emissions from Japanese healthy meals with different protein sources. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1232198>
- Sanderson, V., Bamber, N., & Pelletier, D. N. (2019). Cradle-to-market life cycle assessment of Okanagan (Canada) cherries: Helicopters, seasonal migrant labour and flying fruit. *Journal of Cleaner Production*, 229, 1283–1293. <https://doi.org/10.1016/j.jclepro.2019.04.398>
- Schaubroeck, T., Ceuppens, S., Luong, A. D., Benetto, E., De Meester, S., Lachat, C., & Uyttendaele, M. (2018). A pragmatic framework to score and inform about the environmental sustainability and nutritional profile of canteen meals, a case study on a university canteen. *Journal of Cleaner Production*, 187, 672–686. <https://doi.org/10.1016/j.jclepro.2018.03.265>
- Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., & Witthöft, C. (2017). Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. *Journal of Cleaner Production*, 140, 470–478. <https://doi.org/10.1016/j.jclepro.2016.06.115>

- Sonnemann, G., Gemechu, E. D., Sala, S., Schau, E. M., Allacker, K., Pant, R., Adibi, N., & Valdivia, S. (2018). Life Cycle Thinking and the Use of LCA in Policies Around the World. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 429–463). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_18
- Starck, C. S., Blumfield, M., Keighley, T., Marshall, S., Petocz, P., Inan-Eroglu, E., Abbott, K., Cassettari, T., Ali, A., Wham, C., Kruger, R., Kira, G., & Fayet-Moore, F. (2021). Nutrient Dense, Low-Cost Foods Can Improve the Affordability and Quality of the New Zealand Diet—A Substitution Modeling Study. *International Journal of Environmental Research and Public Health*, 18(15), 7950. <https://doi.org/10.3390/ijerph18157950>
- Stats NZ. (2024). *Irrigated Land in New Zealand: Data to 2022*. <https://www.stats.govt.nz/indicators/irrigated-land-data-to-2022/>
- Strid, A., Hallström, E., Sonesson, U., Sjons, J., Winkvist, A., & Bianchi, M. (2021). Sustainability Indicators for Foods Benefiting Climate and Health. *Sustainability*, 13(7), Article 7. <https://doi.org/10.3390/su13073621>
- Svanes, E., & Johnsen, F. M. (2019). Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. *Journal of Cleaner Production*, 238, 117773. <https://doi.org/10.1016/j.jclepro.2019.117773>
- Takacs, B., Stegemann, J. A., Kalea, A. Z., & Borrion, A. (2022). Comparison of environmental impacts of individual meals—Does it really make a difference to choose plant-based meals instead of meat-based ones? *Journal of Cleaner Production*, 379, 134782. <https://doi.org/10.1016/j.jclepro.2022.134782>
- Tayleur, C., Balmford, A., Buchanan, G. M., Butchart, S. H. M., Corlet Walker, C., Ducharme, H., Green, R. E., Milder, J. C., Sanderson, F. J., Thomas, D. H. L., Tracewski, L., Vickery, J., & Phalan, B. (2018). Where are commodity crops certified, and what does it mean for conservation and poverty alleviation? *Biological Conservation*, 217, 36–46. <https://doi.org/10.1016/j.biocon.2017.09.024>
- thinkstep ANZ. (2021). *Life cycle assessment of New Zealand mussels and oysters*. <https://www.thinkstep-anz.com/assets/Whitepapers-Reports/Aquaculture-NZ-shellfish-LCA-report-2021-10-20-FINAL.pdf>
- thinkstep ANZ (2023). *LCA of assessment of New Zealand-farmed King salmon*. <https://www.mpi.govt.nz/dmsdocument/57175-LCA-of-NZ-farmed-King-salmon-Full-report/> (Accessed 17 October 2024)

- UNEP. (2017). *Sustainable consumption and production policies*. UNEP - UN Environment Programme. <http://www.unep.org/explore-topics/resource-efficiency/what-we-do/sustainable-consumption-and-production-policies> (Accessed 21 July 2024)
- UNFSS, FAO, ITC, UNCTAD, UNEP, & UNDO. (2020). *Scaling up Voluntary Sustainability Standards through Sustainability Public Procurement and Trade Policy*. https://unctad.org/system/files/official-document/unfss_4th_2020_en.pdf
- United Nations. (2023). *UN Climate Change Conference—United Arab Emirates / UNFCCC*. <https://unfccc.int/cop28> (Accessed 7 June 2024)
- University of Otago, & Ministry of Health. (2011). *A focus on nutrition: Key findings of the 2008/09 New Zealand Adult Nutrition Survey*. Available for download at: <https://www.health.govt.nz/publications/a-focus-on-nutrition-key-findings-from-the-200809-nz-adult-nutrition-survey>
- U.S. Department of Agriculture. (2023). *MyPlate / U.S. Department of Agriculture*. <https://www.myplate.gov/> (Accessed 20 August 2025)
- U.S. Green Building Council. (2025). *LEED rating system / U.S. Green Building Council*. <https://www.usgbc.org/leed> (Accessed 15 August 2025)
- Van Zelm, R., Larrey-Lassalle, P., & Roux, P. (2014). Bridging the gap between life cycle inventory and impact assessment for toxicological assessments of pesticides used in crop production. *Chemosphere*, 100, 175–181. <https://doi.org/10.1016/j.chemosphere.2013.11.037>
- Van Zwieten, L., Rust, J., Kingston, T., Merrington, G., & Morris, S. (2004). Influence of copper fungicide residues on occurrence of earthworms in avocado orchard soils. *The Science of the Total Environment*, 329(1–3), 29–41. <https://doi.org/10.1016/j.scitotenv.2004.02.014>
- Vatsanidou, A., Fountas, S., Liakos, V., Nanos, G., Katsoulas, N., & Gemtos, T. (2020). Life Cycle Assessment of Variable Rate Fertilizer Application in a Pear Orchard. *Sustainability*, 12(17), 6893. <https://doi.org/10.3390/su12176893>
- Waikato Regional Council. (2020). *Farm environment plans for consented farms*. <https://www.waikatoregion.govt.nz/assets/WRC/WRC-2019/6356-HRWO-Factsheets-2020-Farm-Environment-Plans-for-Consented-Farms.pdf>
- Waikato Regional Council. (2025). *Peat subsidence*. Waikato Regional Council. <https://www.waikatoregion.govt.nz/environment/land-and-soil/land-and-soil-monitoring/peat-subsidence-report-card/> (Accessed 15 August 2025)

- WBSCD. (2021). *Food Labeling: Principles to support the uptake of healthy and sustainable diets*. Available for download at: <https://www.wbcsd.org/resources/principles-to-support-the-uptake-of-healthy-and-sustainable-diets/>
- Weidema, B. P., & Stylianou, K. S. (2020). Nutrition in the life cycle assessment of foods—Function or impact? *The International Journal of Life Cycle Assessment*, 25(7), 1210–1216. <https://doi.org/10.1007/s11367-019-01658-y>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., ... Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Winther, U., Hognes, E. S., Jafarzadeh, S., & Ziegler, F. (2020). *Greenhouse gas emissions of Norwegian seafood products in 2017*. https://www.sintef.no/contentassets/25338e561f1a4270a59ce25bcbc926a2/report-carbon-footprint-norwegian-seafood-products-2017_final_040620.pdf
- Schlatter, B., Trávníček, J., Helbing, M., & Willer, H. (2025). Current Statistics on Organic Agriculture Worldwide: Area, Operators, International Trade and Retail Sales. In: H. Willer, J. Trávníček, & B. Schlatter. (Eds.), *The World of Organic Agriculture. Statistics and emerging trends 2025* (pp. 32-100). FiBL and IFOAM Organics International.
- World Health Organization (WHO). (2023). Total fat intake for the prevention of unhealthy weight gain in adults and children: WHO guideline. Available for download at: <https://www.who.int/publications/i/item/9789240073654>
- Zonderland-Thomassen, M. A., & Ledgard, S. F. (2012). Water footprinting – A comparison of methods using New Zealand dairy farming as a case study. *Agricultural Systems*, 110, 30–40. <https://doi.org/10.1016/j.agsy.2012.03.006>
- Zonderland-Thomassen, M. A., Lieffering, M., & Ledgard, S. F. (2014). Water footprint of beef cattle and sheep produced in New Zealand: Water scarcity and eutrophication impacts. *Journal of Cleaner Production*, 73, 253–262. <https://doi.org/10.1016/j.jclepro.2013.12.025>

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Appendix A – Chapter 1

Table A1 List of mainstream agri-food VSS with details of performance indicators in their criteria (several quoted directly from respective publicly available standards)

Name of VSS	Criterion with performance metric	Indicator	LCA based?
Red Tractor Fresh fruit standard v5 (2022)	Yes. Recommended that on-farm energy use is monitored.	Energy use records. Recommendation: To help monitor and measure your GHG emissions you can visit an online calculator e.g. http://www.cffcboncalculator.org.uk , https://coolfarmtool.org/coolfarmtool/	Partially. Framework not based on international standards like ISO or GHG protocol, but considers scope 1,2,3 emissions. Farmers can choose if they want to include or exclude scope 3.
Red Tractor Beef and Lamb Standard (2022) v 5	None	-	-
Red Tractor Dairy Standards (2022) v 5	None	-	-
Red Tractor Combinable crops and sugarbeet Standards (2022) v 5	None	-	-
LEAF Marque	Soil health is measured There is an annual Energy Audit.	Earthworm counts, or a measure justified by the business • Audit records a measurement for each major energy use (e.g. drying, heating, livestock housing, field	No No

	Energy consumption is monitored	operations)	
	On farm Greenhouse Gas (GHG) emissions are recorded.	• Energy consumption is recorded at least quarterly • The most significant use(s) of energy identified in the Energy Audit (see 6.1) are measured • Energy use is measured per unit of output or other relevant metric (kWh per tonne/head/hectare)	No
	A carbon footprinting tool is used	• There is an annual record of GHG emissions based on energy consumption records (see 6.1 and 6.2) as a minimum; reference to emissions from livestock and their feed, where applicable	No
	Applied water use efficiency is measured.	• Carbon footprinting calculations are made on an annual basis • Results from carbon footprinting are used to establish a baseline to identify opportunities for improvement • Footprinting may include direct emissions controlled by the farm (Scope 1): - tractors - farm machinery - change of land use - methane emissions from livestock, where applicable - leaks from refrigeration - sequestration off-setting potential from environmental features (e.g. waterbodies, peat, trees, etc.)	Depends on the tool used
	Water quality is	• Water use efficiency of all irrigated water is measured in litres (or m3) of water per tonne of	No

	monitored.	output • Measurements are taken and recorded at least quarterly or at a frequency justified by the business	No
Origin Green Beef and Lamb Assurance Scheme	GHG emissions and carbon footprint	Calculations are performed on the Bord Bia database using the combined data in accordance with the accredited Bord Bia Carbon Footprint Model. These calculations provide the carbon footprint of the meat produced. This is a key indicator of the sustainability of the farm.	Yes. PAS 2050: 2011 - Specification for the assessment of the life cycle of GHG emissions of goods and services.
Origin Green Sustainable Dairy Assurance Scheme	Participate in existing environmental development / protection scheme(s).	During the farm visit the auditor will collect additional information about the farming enterprise that will enable milk processors to substantiate claims with regard to carbon footprint, water use, etc. and this information will be used by Bord Bia to assess the sustainability performance of the farm. Bord Bia and Teagasc have developed a Carbon Navigator tool that farmers can use to improve financial performance while reducing the carbon footprint of their farms. The sustainability information collected on grazing season length, breeding details, calving intervals, fertiliser & energy use, manure management and milk production will provide information to farmers on their current performance. Using the Carbon Navigator farmers can set themselves targets in each key area and see the potential impact of reaching these targets in terms of reduced costs and enhanced environmental performance.	Yes. PAS 2050: 2011 -Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
Origin Green Sustainable Egg Assurance	-	-	-

Scheme			
Origin Green Sustainable Poultry products Assurance Scheme	GHG, energy use, and water use is measured (m3 of water used)	PAS 2050: 2011 - Specification for the assessment of the life cycle of GHG emissions of goods and services. Requires growers, breeders etc to input data for several criteria, including total amount of chemicals used, energy consumption, and water use.	Yes
Origin Green Sustainable Horticulture Assurance Scheme	Recording and monitoring of energy use is required.	Inputs required to be made by grower for several variables including fuel, electricity, fertiliser, pesticides, growing media, packaging, refrigerant used in attached coolstores, waste materials. GHG calculations not specified in the document anywhere. No mention of the carbon navigator tool either.	-
Global G.A.P. Integrated Farm Assurance (IFA) aquaculture (finfish, crustacean, molluscs, seaweed – v6 (2024))	No	No	-
Global G.A.P. Integrated Farm Assurance (IFA) all crops base	No	No	-
Global G.A.P. Integrated Farm	No	No	-

Assurance (IFA) combinable crops – v5.2 (2019)			
Global G.A.P. Integrated Farm Assurance (IFA) Fruits and vegetables v6 - (2024)	Management of biodiversity is supported by metrics On farm energy use is monitored and based on this, energy management is supported by metrics The farm contributes to reducing GHG emissions from the atmosphere and these efforts are supported with metrics	Acceptable metrics allow calculating at minimum: total area of natural and semi natural ecosystems or habitats, legally recognised protected areas, or areas effectively protected by other means; total area converted to agricultural use or other uses; total area that has already been restored; total area that is under restoration or being planned for binding restoration Acceptable metrics allow for the calculation of at minimum: total energy use on the farm for each energy source/month; proportion of renewable vs non-renewable energy in the energy source. Additional calculations can include for example: amount of energy imported into the farm from the grid; amount of energy exported to the grid; amount of energy generated at producer level for example via solar panels Acceptable metrics include the following: at minimum, the GHG equivalence of the total amount of energy use on the farm (per ha/month or per kg/month) Additional calculations can include GHG equivalents of other amounts of energy calculated for the farm. GHG equivalence as related to soil and biomass, carbon farming, or environmental	No No Optional – only if carbon footprint based on LCA methods are opted for. Not explicitly stated in the document, but wording overall has a farm and scope 1 focus. No

	Fertiliser management is supported by metrics	footprint. Metrics should refer to the farms various production sites, units of time (growing cycles), and to GHG per kg of product or per hectare of production.	
	Water management is supported by metrics	Acceptable metrics include the following: total amounts of potassium, nitrogen, and phosphorous applied on the farm (in kg/crop, /month, and /ha/month) Metrics should refer to organic and inorganic fertilisers, units of time (growing cycle), and amounts of fertiliser per kg of product and per hectare of production.	No
	Management of PPP is supported with metrics	Acceptable metrics allow calculating the following: at minimum, the total monthly amount of water used on the farm in agricultural production (m3/site/month); the amount of water abstracted from specific sources should also be listed. Additional metrics may include, for example: monthly amount of water used in irrigation/ha – indicators should refer to water sources (excluding rainwater), units of time (growing cycle), and the amounts of water used per kg of product and hectare of production. Acceptable metrics allow calculating the following: total amount of active ingredients applied (in kg/crop, kg/month, and	No

		kg/hectare/month). Metrics should refer to the farm's various production sites, units of time (growing cycles), and the active ingredient amounts per kg of product and per hectare of production.	
Responsible Wool Standard v2.2 (2021)	No	No	-
ZQ Merino	No	No	-
MSC v3.0 (2022)	No	No	-
ASC farm standard (multiple species, example salmon) 1.4.1 (2024)	Free sulfide levels.	Acceptable levels of total "free" sulfide in surficial sediment (0-2 centimeters from the surface) measured beneath sea-based farms ($\leq 1,500 \mu\text{M}$, monitoring every five years ⁵ is required. ($\geq 1,500 \mu\text{M}$ and $\leq 3,000 \mu\text{M}$, monitoring every year is required.)	No
		Unacceptable levels of total "free" sulfide in surficial sediment measured beneath sea-based farms ($\geq 3,000 \mu\text{M}$).	No
		Annual median concentration of total ammonia nitrogen in effluent or receiving water beyond mixing zone ($<0.6 \text{ mg/L}$).	No
	Total ammonia nitrogen	Annual median concentration of total suspended solids in effluent compared to influent measured in the outflow or in the receiving water beyond zone of initial dilution ($<5 \text{ mg/L}$)	No
	Forage feed	Forage Fish Equivalency Ratio (FFER) for abalone fed manufactured feed.	No

	Energy use	Records of energy used on farm per ton of production need to be provided	No
ASC Bivalve standard v 1.1 (2019)	Free sulfide levels.	Acceptable levels of total “free” sulfide in surficial sediment (0-2 centimeters from the surface) measured beneath sea-based farms ($\leq 1,500 \mu\text{M}$, monitoring every five years ⁵ is required. ($\geq 1,500 \mu\text{M}$ and $\leq 3,000 \mu\text{M}$, monitoring every year is required.)	No
		Unacceptable levels of total “free” sulfide in surficial sediment measured beneath sea-based farms ($\geq 3,000 \mu\text{M}$).	No
	Energy Use	‘Evidence of energy use monitoring relative to production and ongoing effort to improve efficiency’ and ‘Maintenance records for farm equipment (e.g., boats and generators) are up to date and available’	No
ASC Flatfish standard v1.1 (2023)	Free sulfide levels	Redox potential or total ‘free’ sulphide levels in sediment immediately outside of the Allowable Zone of Effect (AZE) attributed to farm operations (Redox potential > 0 millivolts (mV) OR Sulphide $\leq 1,500$ microMoles / l OR No significant difference in redox potential or total ‘free’ sulphide levels in sediment at the edge of the AZE in comparison to control sites	No
	Benthic fauna	Benthic faunal index score (choosing a suitable benthic index to the composition of the benthos being sampled) (AZTI Marine Biotic Index (AMBI7) score ≤ 3.3 , or Shannon-Wiener Index score > 3 , or Benthic	No

		Quality Index (BQI) score ≥ 15, or Infaunal Trophic Index (ITI) score ≥ 25 or BENTIX8 score ≥ 3.5 OR No significant difference in benthic faunal index scores at the edge of the AZE in comparison to control site	
	Copper levels	Evidence that copper (Cu) levels are < 34 mg Cu/kg dry sediment weight OR In instances where the copper in the sediment exceeds 34 mg Cu/kg dry sediment weight, demonstration that the Cu concentration is not significantly different compared to background concentrations as measured at three reference sites in the water body	No
	Water quality	Dissolved oxygen (DO) - Weekly average percent saturation10 of dissolved oxygen (DO) on farm ($\geq$ 70%)	No
		Maximum percentage of weekly samples from DO concentration indicator that fall under 2 mg/litre DO (5%)	No
		Total suspended solids (TSS) - Annual median concentration of TSS in effluent compared to influent measured in the outflow or in the receiving water beyond zone of initial dilution <5mg/L	No
		Total ammonia – Annual median concentration of total ammonia nitrogen in effluent or receiving water beyond	No

		mixing zone (<0.6 mg/L)	
		BOD - ≤ 30 mg/L average and no higher than 50 mg/L	No
	Effluents	TSS - ≤ 30 mg/L average and no higher than 50 mg/L	No
		Total Ammonia Nitrogen - ≤ 1 mg/l average and no higher than 1.5 mg/L	No
	Sludge Disposal and Salinisation of Freshwater and Soil Resources – Chloride concentration	Water-specific conductance or chloride concentration in freshwater wells used by the farm or located on adjacent properties (For all freshwater wells (identified prior to full assessment), specific conductance may not exceed 1,500 mhos per centimetre and/or chloride concentration may not exceed 300 mg/l)	No
	Use resources in an environmentally efficient and responsible Manner	Fishmeal and fish oil Forage Fish Dependency Ratio (FFDR _m and FFDR _o) for grow-out ((calculated using formulas in Appendix 2)	No
	Responsible origin of non-marine raw materials in feed	Percent of non-marine ingredients from sources certified by an ISEAL Member's certification scheme that addresses environmental and social sustainability (80% for soy and palm oil from June 2024)	No
	Energy use and GHG	Presence of an energy use assessment	Yes - Assessments shall follow either the GHG Protocol Corporate

	emissions	verifying the energy consumption on the farm and representing the production cycle, as outlined in Appendix 3 (measured in kilojoule/tonne of fish per production cycle) Records of GHG emissions and evidence of an annual GHG assessment and reporting to ASC, as outlined in Appendix 3 Documentation of GHG emissions of the feed used during the previous production cycle reported to ASC, as outlined in Appendix 3 Accounting for GHG emissions from feed	Standard or ISO 14064-1 Yes – as above Yes – as above More details in standard document appendix 3 Yes. GHG protocol corporate standard or ISO14040/14044
ASC freshwater trout standard v1.2 (2019)	Land-based systems - Water Use/Abstraction Levels Land-based systems - Water Quality/Effluent Cage-Based Systems - Water quality/benthic Community	Maximum amount of water that a farm can divert from a natural flowing water body (such as a river or stream) (50% of the natural water body's flow immediately above the farm) Maximum total amount of phosphorus released into the aquatic environment per tonne (t) of fish produced over the previous 12-month period (see methodology in Appendix II-A) (4 kg/t of fish produced) Minimum oxygen saturation in the outflow, measured monthly (see methodology in Appendix IIB) (60%) Maximum baseline total phosphorus concentration of the water body (see Appendix II-H) ($\leq 20 \mu\text{g/L}$)	No No No No

		Minimum per cent oxygen saturation of water 50 centimetres above bottom sediment (at all oxygen monitoring locations described in Appendix II-G) ($\geq 50\%$)	No
		Maximum allowed increase in total phosphorus concentration in lake from baseline (25% for water bodies with a surface area of less than 1,000 km ² ; 15% for water bodies with a surface area of 1,000 km ² or greater)	No
		Maximum total amount of phosphorus released into the environment per metric ton (t) of fish produced over the previous 12-month period (see Appendix II-A) (4 kg/t of fish produced)	No
	Responsible origin of marine raw materials	The Fishsource score required for the fisheries from which marine raw material in feed is derived (excluding trimming and by-products) (All individual scores ≥ 6 , and "Current Health" score ≥ 6)	No
		Fishmeal Forage Fish Dependency Ratio (FFDR _m) for grow-out (calculated using formulas in Appendix III, subsection 1) (≤ 1.5)	No
	Dependency on wild-caught marine ingredients in feed	Compliance with one of the two following requirements: a) Fish Oil Forage Fish Dependency Ratio (FFDR _o) for grow-out (calculated using formulas in Appendix III, subsection 1) (a) ≤ 2.95),	No

		or, b) Maximum level of EPA/DHA content from marine sources as a percentage of fatty acids in the feed (excluding EPA/DHA from trimmings and by-products) ($\leq 9\%$)	
ASC Pangasius standard v1.2 (2019)	Water use	For ponds, maximum ratio of total water abstracted (not consumed) per tonne of fish produced. Calculate abstracted water using formula in Annex D. (5,000 m ³ /metric ton of fish produced)	No
	Total Phosphorous (TP)	For cages and pens, maximum amount of TP added as feed per metric ton of fish produced (20 kg/t)	No
	Total Nitrogen (TN)	For ponds, amount of TP discharged per metric ton of fish produced (See TP measurement methodology and calculation in Annex D) (7.2 kg/t)	No
		For cages and pens, maximum amount of TN added as feed per metric ton of fish produced (70 kg/t)	No
		For ponds, amount of TN discharged per metric ton of fish produced (See TN measurement methodology and calculation in Annex D) (27.5 kg/t)	No
	Measuring water quality in receiving water body	Percentage change in diurnal DO of receiving waters relative to DO at saturation for the water's specific salinity and temperature ($\leq 65\%$).	No
	Measuring quality of pond effluents		

	Energy Consumption	Maximum average percentage change of TP between inlet and outlet (See TP measurement methodology and TP discharge formula in Annex D) (100%)	No
		Maximum average percentage change of TN between inlet and outlet (See TN measurement methodology and TN discharge formula in Annex D) (70%)	No
		Minimum dissolved oxygen (DO) concentration in water discharged (See DO measurement methodology in Annex D) (3 mg/l).	No
	Sustainability of feed ingredients	Evidence of an energy use assessment of on-farm energy consumption, measured in kilojoule/t fish/year.	No
		Fishmeal or fish oil products used in feed have been sourced from fisheries with an average FishSource (FS) score (≥ 6.0 for all categories)	No
	Efficient management of feed use on the farm	Maximum weighted average of economic Feed Conversion Ratio (eFCR) for the complete production cycle (1.68)	No
		Maximum Fish Feed Equivalence Ratio (FFER) (0.5)	No
ASC Standard salmon v 1.4.1 (2024)	Benthic biodiversity and benthic effects	Redox potential or 5 sulphide levels in sediment outside of the Allowable Zone of Effect (AZE), following the sampling methodology outlined in Appendix I-1 (Redox	No

	Faunal index	potential > 0 mV, or, Sulphide $\leq 1,500 \mu\text{Mol /L}$)	
		Faunal index score indicating good to high ecological quality in sediment outside the AZE, following the sampling methodology outlined in Appendix I-1 (AZTI Marine Biotic Index (AMBI) score ≤ 3.3 , or, Shannon Index score > 3, or, Benthic Quality Index (BQI) score ≥ 15 , or, Infaunal Trophic Index (ITI) score ≥ 25)	No
		Number of macrofaunal taxa in the sediment within the AZE, following the sampling methodology outlined in Appendix I-1 (≥ 2 highly abundant7 taxa that are not pollution indicator species)	No
		Weekly average percent saturation of DO on farm, calculated following methodology in Appendix I-4 ($\geq 70\%$)	No
	Water quality in and near the site of operation	Maximum percentage of weekly samples from above that fall under 2 mg/L DO (5%)	No
		Percentage of fines in the feed at point of entry to the farm (calculated following methodology in Appendix I-2) (< 1% by weight of the feed)	No
	Nutrient release from production	Fishmeal Forage Fish Dependency Ratio (FFDRm) for grow-out (calculated using formulas in Appendix IV- 1) (<1.2)	No
		Fish Oil Forage Fish Dependency Ratio (FFDRo) for grow-out (calculated using formulas in Appendix IV- 1), or,	No

	Use of wild fish for feed Source of non-marine raw materials in feed Energy consumption and GHG emissions on farms	Maximum amount of EPA and DHA from direct marine sources (calculated according to Appendix IV-2) (FFDRo < 2.52, or, (EPA + DHA) < 30 g/kg feed) Percentage of soya or soya-derived ingredients in the feed that are certified by the Roundtable for Responsible Soy (RTRS) or equivalent (100%) Records of GHG emissions on farm and evidence of an annual GHG assessment, as outlined in Appendix V-1 Documentation of GHG emissions of the feed used during the previous production cycle, as outlined in Appendix V, subsection 2.	No Yes. Yes. Both above Assessments shall follow either the GHG Protocol Corporate Standard or ISO 14064-1
ASC seabass, seabream and meagre standard v 1.1 (2019)	Benthic biodiversity and effects	Redox potential or total 'free' sulphide levels in sediment immediately outside of the Allowable Zone of Effect (AZE) attributed to farm operations (Redox potential > 0 millivolts (mV) OR Sulphide ≤ 1,500 microMoles / l) Benthic faunal index score (AZTI Marine Biotic Index (AMBI7) score ≤ 3.3, or Shannon-Wiener Index score > 3, or Benthic Quality Index (BQI) score ≥ 15, or Infaunal Trophic Index (ITI) score ≥ 25 or BENTIX8 score ≥ 3.5) Evidence that copper levels are < 34 mg Cu/kg dry sediment weight Weekly average percent saturation¹⁰ of DO on farm (Appendix 1-2) (≥ 70%)	No No No

	Water quality in and near the site of operation	Maximum percentage of weekly samples ¹² from above criterion that fall under 2 mg/liter DO (Appendix 1-2) (5%)	No
	Efficient and optimized diets	Fishmeal Forage Fish Dependency Ratio (FFDR _m) for grow-out (calculated using formulas in Appendix 2) ((a) <i>Dicentrarchus labrax</i> and <i>Sparus aurata</i> : ≤ 1.85 (b) <i>Argyrosomus regius</i> : ≤ 2.75, ≤ 2.5 (3 years ⁴⁵), ≤ 2.35 (6 years) (c) <i>Pagrus major</i> : ≤ 4.5, ≤ 3.5 (3 years ⁴⁶), ≤ 2.5 (6 years))	No No
	Energy consumption and GHG gas emissions on farms	Fish Oil Forage Fish Dependency Ratio (FFDR _o) for grow-out (calculated using formulas in Appendix 2) (All species: ≤ 3, ≤ 2.95 (3 years ⁴⁶), ≤ 2.9 (6 years)) Records of GHG emissions and evidence of an annual GHG assessment and reporting to ASC, as outlined in Appendix 3 Documentation of GHG emissions of the feed used during the previous production cycle reported to ASC, as outlined in Appendix 3	No Yes. Assessments shall follow either the GHG Protocol Corporate Standard or ISO 14064-1 Yes. A cradle-to-gate assessment, taking into account upstream inputs and the feed manufacturing process, according to the GHG Product Standard 2. An LCA following the ISO 14040 and 14044 requirements for life cycle assessments.
ASC Seriola and cobia standard v 1.1 (2019)	Efficient and optimised diet	(a) Fishmeal Forage Fish Dependency Ratio (FFDR _m) and Fish Oil Forage Fish Dependency Ratio (FFDR _o) for <i>Seriola</i> (calculated using formulae in Appendix 1). Kampachi (<i>S. rivoliana</i> , <i>S. dumerili</i>), Hamachi (<i>S. quinquerediata</i>)	No

	Responsible origin of marine raw materials	(Kampachi: $FFDRm \leq 2.9/FFDRo \leq 2.9$ Hamachi: $FFDRm \leq 6.0/FFDRo \leq 7.0$ (now) $FFDRm \leq 4.8/FFDRo \leq 5.0$ (3 years) $FFDRm \leq 2.9/FFDRo \leq 2.9$ (6 years) (b) $FFDRm$ and $FFDRo$ cobia (calculated using formulae in Appendix 1) ($FFDRm \leq 6.0/FFDRo \leq 6.0$ (now) $FFDRm \leq 4.0/FFDRo \leq 4.0$ (3 years) $FFDRm \leq 2.9/FFDRo \leq 2.9$ (6 years)) The fishmeal or fish oil used in feed must have a FishSource score of 6.0 or higher, and an 8 in the biomass category or show evidence of being engaged in a credible and time bound fisheries improvement project (FIP) (At least 80% of the fish meal and fish oil used in feed (excluding fishmeal and oil from byproducts) must meet this criteria	No
	Dissolved oxygen on farm	Weekly average percent dissolved oxygen (DO) saturation on farm, calculated in the following methodology ($\geq 70\%$ saturation)	No
ASC Shrimp standard v1.2.1 (2023)	Origin of aquatic and terrestrial feed Ingredients	Percentage of non-marine ingredients from sources certified by an ISEAL member's certification scheme that addresses environmental and social sustainability (80% for soy and palm oil.)	No
	Effluent contaminant load	Nitrogen effluent load per ton of crustacea produced over a 12-month period (see Appendix IX). ($P. monodon$; $<32.4 \text{ kg N/T}$ $P. vannamei$; $<25.2 \text{ kg N/T}$	No

		Cherax spp., Procambarus spp., Astacus spp; <26.1 kg N/T Macrobrachium spp: <39.2 kg N/T) Phosphorous effluent load per ton of crustacea produced over a 12-month period. (P. monodon; <5.4 kg P/T P. vannamei; <3.9 kg P/T Cherax spp., Procambarus spp., Astacus spp: <4.0 kg P/T Macrobrachium spp: <6.1 kg P/T) Treatment of effluent water from permanently aerated ponds. (concentration of settleable solids in effluent water < 3.3 mL/L) Percentage change in diurnal dissolved oxygen (DO) relative to DO at saturation in receiving water body for the water's specific salinity and temperature ($\leq 65\%$) Energy consumption by source over a 12-month period. Annual Cumulative Energy Demand (CED) (mega joules/ton of shrimp produced) over a 12- month period.	No No No No No
ASC Tilapia standard v 1.2 (2019)	The effects of eutrophication Water quality in	The percent change in diurnal dissolved oxygen of receiving waters relative to dissolved oxygen at saturation for the water's specific salinity and Temperature ($\leq 65\%$) Total phosphorus concentration limit in receiving waters ($\leq 20 \mu\text{g/L}$)	No No

	oligotrophic receiving waters	Chlorophyll a concentration limit in receiving waters ($\leq 4.0 \mu\text{g/L}$)	No
	Nutrient efficiency	utilization	
		The total amount of phosphorus added to the culture system per metric ton of fish produced per year. Use equations from Appendix III. ($\leq 27 \text{ kg}$)	No
		The total amount of phosphorus released from the culture system per metric ton of fish produced per year. ($\leq 20 \text{ kg}$)	No
		Calculation and verification of the total amount of nitrogen applied to the culture system. (Measured in kg nitrogen/t fish/year)	No
		Calculation and verification of the total amount of nitrogen released from the farming activity. (Measured in kg nitrogen/t fish/year)	No
		Percent change in specific conductance of freshwater from a drilled well at the time of drilling and the time of audit. This is required when freshwater wells are used in combination with brackish surface water for the culture of tilapia. ($\leq 10 \%$)	No
	Groundwater salinization	Feed Fish Equivalence Ratio (FFER). See Appendix IV for feed calculations. (≤ 0.8)	No
	Use of wild fish for feed (fishmeal and oil)	The average FishSource score characterizing the fishery(ies) from which the fishmeal or fish oil is derived. See Appendix V for explanation of	No

	Energy Use	FishSource scoring. (≥ 6.0 with no individual score < 6.0 or an N/A in the stock assessment category). Identification of the energy sources and calculation and verification of total energy used at the culture facility (Measured in kilojoules/t fish/year)	No
ASC tropical marine finfish standard v 1.1 (2023).	Benthic biodiversity and benthic effects	Redox potential or total 'free' sulphide levels in sediment immediately outside of the Allowable Zone of Effect (AZE) attributed to farm operations (Redox potential > 0 millivolts (mV) OR Sulphide $\leq 1,500$ microMoles / l)	No
		Benthic faunal index score (AZTI Marine Biotic Index (AMBI) score ≤ 3.3 , or Shannon-Wiener Index score > 3 , or Benthic Quality Index (BQI) score ≥ 15 , or Infaunal Trophic Index (ITI) score ≥ 25	No
		Evidence that copper levels are < 34 mg Cu/kg dry sediment weight	No
	Water quality in and near the site of operation	Weekly average saturation percentage 10 of DO on farm ($\geq 70\%$)	No
	Effluents	Biological oxygen demand (BOD) (≤ 30 mg/l average and no higher than 50 mg/l) TSS (≤ 30 mg/l average and no higher than 50 mg/l)	No

	Efficient and optimised diets	Total Ammonia Nitrogen (≤ 1 mg/l average and no higher than 1.5 mg/l) Fishmeal Forage Fish Dependency Ratio (FFDRm) for grow-out (calculated using formulas in Appendix 2) - (a) FFDRm Barramundi ≤ 2.25 (from June 2019), 1.8 (June 2022), 1.4 (June 2025) (b) FFDRm Grouper and Snapper ≤ 3.45 (from June 2019), 3.0 (June 2022), 2.6 (June 2025) (c) FFDRm Pompano ≤ 2.8 (from June 2019), 2.4 (June 2022), 2.0 (June 2025) (d) FFDRm Yellow Croaker ≤ 3.63 (from June 2019), 3.2 (June 2022), 2.9 (June 2025) Fish Oil Forage Fish Dependency Ratio (FFDRo) for grow-out (calculated using formulas in Appendix 2) - (a) FFDRo Barramundi ≤ 2.75 (from June 2019), 2.3 (June 2022), 2.0 (June 2025) (b) FFDRo Grouper and Snapper ≤ 3.55 (from June 2019), 3.0 (June 2022), 2.6 (June 2025) (c) FFDRo Pompano ≤ 2.73 (from June 2019), 2.3 (June 2022), 2.0 (June 2025) (d) FFDRo Yellow Croaker ≤ 4.05 (from June 2019), 3.8 (June 2022), 3.5 (June 2025) Presence of an energy use assessment verifying the energy consumption on the farm and representing the production cycle, as outlined in Appendix 3 (measured in kilojoule/t fish/production cycle)	No No
	Energy consumption and GHG emissions on farms		

		Records of GHG emissions and evidence of an annual GHG assessment and reporting to ASC, as outlined in Appendix 3 Documentation of GHG emissions of the feed used during the previous production cycle reported to ASC, as outlined in Appendix 3 Evidence of a documented strategy to reduce GHG per unit of production (measured in kilojoule/t fish produced)	No
ASC-MSC seaweed standard v 1.01 (2018)	Energy efficiency	Energy sue monitoring – minimum (There is some information about energy use of the production unit.), target (There is evidence of energy use monitoring relative to production and ongoing effort to improve efficiency.)	No
ASC farm standard 2024 draft consultation	Water Quality Scope – Farms using feed or fertilisers and releasing effluents	The UoC shall present the AMA's 24-month WUM baseline monitoring survey, including the parameters DO, Secchi disk (SD) depth, Chl-a, TN and TP nutrient concentrations (Appendix 8 (2.3)) The UoC shall present the WUM-level baseline characterisation (Appendix 8 (2.3.2)) and perform its own farm-level baseline characterisation (Appendix 8 (2.3.1)): 1. Run the 24-month initial WUM baseline monitoring survey (Indicator 2.6.3) through the ASC water quality calculator, to determine the following: - o Limiting nutrient(s); N-, P- or co-limited; - o Trophic status; hyper-eutrophic, eutrophic, mesotrophic, oligotrophic, or ultra-oligotrophic (Appendix 8 (2.3.4)); - o Depths of the zone of	No No

		oxygen depletion ($DO \leq 4\text{mg/l}$) and anoxia ($DO \leq 2\text{mg/l}$); o Modelled BOD. 2. Record the number of (i) adverse turnover events and (ii) harmful algal blooms over the last 10 years (Appendix 8 (2.3.3)). The UoC shall perform quarterly monitoring of DO, TN, TP, SD and Chl-a (Appendix 8 (2.3.1, 2.3.2 and 2.3.5)), to populate the ASC water quality calculator as required in Indicators 2.6.6 -2.6.8. Using the ASC water quality calculator, the UoC shall demonstrate annually that there is no upward transition of trophic status (Appendix 8 (2.3.4)) compared with the initial WUM and farm-level baseline characterisation (Indicator 2.6.4). Using the ASC water quality calculator, the UoC shall demonstrate annually that neither the limiting nutrient(s) nor Chl-a indicate an upward rate of change > 15% at the WUM or farm level over the previous 24 months. The UoC shall ensure that the feed fed contains < 1% fines (Appendix 8 (3.2)). The UoC shall ensure that water released goes through a treatment system capturing $\geq 65\%$ of suspended solids originating from feed or fertiliser used, and that the concentration of settleable solids in effluent water is <3.3ml/L, if any of the following	No No No No

		apply (Appendix 8 (4.2 and 4.3)): - o using aeration over >90% of the production cycle; - o exchanging >10% of culture water per day; - o exchanging all water once per week or more during peak biomass; - o using stocking densities >2kg/m³. Using the ASC water quality calculator, the UoC shall annually estimate the percentage farm effluent flow contribution to the receiving water (RW) flow (m³/sec) (Appendix 8 (1.3)). The UoC shall demonstrate, through daily monitoring of DO concentration and saturation immediately downstream of the farm (diffuse-source effluent release) (Appendix 8 (4.2)) or RWFA (point-source effluent release) (Appendix 8 (4.3)), that the weekly average of daily DO saturation is ≥65% in freshwater and ≥70% in seawater The UoC shall annually demonstrate, using the DO measurements from Indicator 2.6.18, that ≤5% of the weekly averages of daily DO concentrations are 2mg/l. The UoC shall demonstrate, through monthly DO monitoring at RWFA (Appendix 8 (4.3)), that daily diurnal DO (DDDO) fluctuation is ≤65% saturation level.	No No No No

		The UoC shall monitor and record that used freshwater wells do not exceed a specific conductance of 1,500 mhos/centimetre or chloride concentration or 300 milligrams per litre.	No
		The UoC shall monitor and record water levels in groundwater wells, where legally allowed.	No
		The UoC shall record energy inputs to the farm and calculate annually the energy intensity of production, in MJ per tonne of live-weight farm production, following the method outlined in Appendix 9.	No
		The UoC shall calculate annually the GHG emissions intensity of production, in kg CO₂-equivalent (CO₂e) emissions per kg of edible weight of product, following the method outlined in Appendix 9, including emissions associated with: a) On-farm use of energy; b) Production, processing and transport of feed; c) Production of smolts, seed or juvenile inputs; and d) Production of other farm inputs as indicated in Appendix 9.	Yes
		The UoC shall set quantitative GHG emission reduction targets to work towards an emissions intensity below the higher of (a) 7.5kg CO₂-e/kg edible weight or (b) the species-specific CO₂e	Yes

	Freshwater use Energy Use and GHGs (Intent – Farms have a greenhouse gas management plan informed by regular measurement and reporting of on-farm energy use and farm- and feed-related emissions, including meaningful actions to reduce emissions from operations and supply chains.)	benchmark provided in Appendix 9. The UoC shall carry out sampling of copper levels in the sediment, following the method outlined in Appendix 7, to demonstrate copper levels are <34 mg Cu/kg dry sediment weight. In instances where copper levels in sediment exceeds 34 mg Cu/kg dry sediment weight, the UoC shall demonstrate that the levels fall within the range of background concentrations as measured at three reference locations. The farm site shall annually report to ASC the feed properties, feed use and calculated feed efficiency values, in accordance with ASC data submission procedures.	No No
ASC feed standard 2023	Water use	The UoC shall calculate, record and, using the template provided on the ASC website, annually report to ASC its water consumption per water source in megalitres/t (total) product produced/year (using the methodology as outlined in Annex 2, section A1). Where wells are used, groundwater levels shall	No

	Waste management	be measured and recorded on a regular basis (taking into account seasonal fluctuation) and at least once a year.	No
		The UoC shall calculate, record and, using the template provided on the ASC website, annually report to ASC its waste in tonne (t) per year per method of disposal (using the methodology as outlined in Annex 2, section A4).	No
		The UoC shall calculate and, using the template provided on the ASC website, annually report to ASC its effluent discharge in megalitres (ML) per year per destination (using the methodology as outlined in Annex 2, section A2); the recording shall include all incidences of spills or accidental discharges	No
		The UoC shall calculate, record and, using the template provided on the ASC website, annually report to ASC its energy consumption in megajoules (MJ) per tonne of (total) product produced in the assessed year (using the methodology as outlined in Annex 2, section A3).	No
	Energy use and GHG emissions	The UoC shall calculate, record and, using the template provided on the ASC website, report (publicly ¹²⁵ and to ASC) its Greenhouse Gas (GHG) emissions in kg CO ₂ equivalents per tonne of (total) product produced/year (using the methodology as outlined in Annex 2, section B).	Yes. GHG Protocol is used to calculate scope 1,2,3 emissions
Rainforest Alliance v 1.3	Conservation and Enhancement of Natural	Mandatory Smart Meter: If there is less than 10% of the total area under natural vegetation cover	No

(2020)	Ecosystems and Vegetation	or less than 15% for farms growing shade-tolerant crops, management sets targets and takes actions for farms to reach these thresholds as required in 6.2.4. (Indicator is % of total farm area under natural vegetation cover) Self-selected Smart Meter: Farms with shade-tolerant crops work towards agroforestry systems with optimal shade coverage diversity according to the Shade coverage and species diversity reference parameters. (Indicators include % shade cover averaged over the portion of the farm or group of farms growing shade-tolerant crops; and average number of shade tree species per hectare growing shade-tolerant crops) Mandatory Smart Meter: Irrigation and water distribution systems are managed to optimize crop productivity considering at least the following factors: • Crop evapotranspiration at different growth stages • Soil conditions • Rainfall pattern Producers record the amount of water used for irrigation from year one onwards. (Indicator: Water use for processing in total and per unit of the product leaving the farm (L, L/Kg) Mandatory Smart Meter: Management sets targets for increased efficiency in energy use and for reduced dependency on non-renewable	No No No
	Water Management and Conservation		

	Energy Efficiency GHG emissions reduction	energy sources. The progress is monitored and reported yearly. For Group Management, this is applicable if groups have energy use for processing. Indicators: • Amounts of renewable and non-renewable energy used, by type (e.g., volume of fuel, kWh electricity, quantity of biomass energy) • Total energy use • Total energy use per kg of product Self-Selected Smart Meter: Producers document net Greenhouse Gases (GHG) emissions from main sources in production and processing operations. This includes emissions from use of fossil fuels and electricity, fertilizer, waste and wastewater and land use change. Producers establish GHG reduction targets, develop and implement a strategy to meet these targets, and monitor annually against these targets. Indicators: • Total annual net GHG emissions from the above indicated sources (tons of CO₂e) • Net GHG emissions from the above indicated sources per unit of the final farm product (tons of CO₂e per unit)	No Partially. Framework not based on international standards like ISO or GHG protocol, but considers scope 1,2,3 emissions. Farmers can choose if they want to include or exclude scope 3.
Fairtrade International Standard for Small-scale Producer	No	No	-

Organizations v2.8 (2019)			
Proterra v5 (2023)	No	No	-
Bonsucro Production standard (agriculture and milling) v 5.2 (2023)	To monitor global warming emissions with a view to minimising climate change impacts	The operator ensures that GHG emissions per tonne of cane are below the metric threshold (<40 kg CO₂eq/t cane). The operator shall estimate the emissions from agricultural activities using the Bonsucro calculator and ensure GHG emissions are below the threshold. The result is also used in the calculation of the total emissions field-to-gate. The operator ensures that GHG emissions per tonne of sugar are below the metric threshold (Total <0.4 t CO₂eq/t sugar). The operator shall estimate emissions from industrial activities using the Bonsucro calculator and ensure GHG emissions are below the threshold. This indicator is applicable only when sugar is produced. Emissions are field-to-gate. The environmental burden is tonnes of carbon dioxide equivalent per tonne of sugar. The operator ensures that GHG emissions per MJ of ethanol are below the metric threshold (Total <24 g CO₂eq/MJ fuel). The operator shall estimate emissions from industrial activities using the	Yes. The Bonsucro Calculator is based on LCA and uses data from various databases including the GREET model, DEFRA, and ecoinvent 3.8 Yes. The Bonsucro Calculator is based on LCA and uses data from various databases including the GREET model, DEFRA, and ecoinvent 3.8 Yes. The Bonsucro Calculator is based on LCA and uses data from various databases including the GREET model, DEFRA, and ecoinvent 3.8 No No

		Bonsucro calculator and ensure GHG emissions are below threshold. This indicator is only applicable when ethanol is produced. The environmental burden is grams of CO2 equivalent per MJ fuel. The operator maximises the energy return on energy invested (>7 energy output/energy input). The operator shall calculate the ratio between the energy delivered by ethanol and the energy invested in the production of the ethanol. The ratio of energy output to energy input shall be greater than 7. This indicator only applies when: • ethanol is produced or • ethanol and electricity are produced.	No No
	A Soil Management Plan is in place to avoid erosion, and maintain and improve soil health	The operator applies as much fertiliser as recommended by soil or leaf analysis (<1.05 ratio of fertiliser applied to recommendation for each nutrient)	No
	The operator maximises water efficiency per mass of product.	The operator shall maximise water efficiency per mass of product (<20 for sugar only, or <30 for ethanol (kg of water/ kg of mass product). The volume of water consumed at the mill equals the volume of water used less the volume of water returned to the environment.	No
	The operator maximises irrigation productivity.	The operator shall ensure irrigated water is used efficiently ($WP_a \geq WP_o$). Water productivity (WP) is a measure of how effectively irrigation	No

	The operator minimises detrimental effects of waste discharge The operator maximises the efficiency of agrochemicals applied.	water is used to produce sugarcane. WP equals the cane yield harvested (t/ha), divided by the net irrigation over the growing season (mm). Irrigation WP is strongly influenced by the amount of rain received. This relationship is expressed as the benchmark WP (WPo). The actual cane yield and net irrigation applied over the growing season (mm) will determine the actual WP (WPa). The operator shall measure the effects of waste in the case of effluent discharge into receiving streams (>2.5 PPM for DO; or ≤ 1 kg COD / t product; or ≤ 0.25 kg BOD / t product). Dissolved oxygen (DO) is an indicator of the quantity of oxygen available in the receiving stream to support life. Sampling for DO shall be from the receiving stream. Sampling for chemical oxygen demand (COD) and biological oxygen demand (BOD) shall be at the discharge point. The operator shall account for quantities of active ingredients in applied agrochemicals (including but not limited to insecticides, acaricides, herbicides, fungicides, nematicides, molluscicides, rodenticides, ripeners and plant-growth regulators excluding coadjuvants and other inert materials).	No No
BCI	No	No	-
CMiA	The environmental management plan should include monitoring	The environmental management plan for the ginny incorporates a monitoring protocol to track the effectiveness of the mitigation	No

	protocols to track the effectiveness of mitigation measures.	measures through a set of indicators (e.g. waste or energy consumption).	
RSPO	Pesticide use Practices maintain the quality and availability of surface and groundwater. Plans to reduce pollution and emissions, including greenhouse gases (GHG), are developed, implemented and monitored and new developments are designed to minimise GHG emissions. Practices maintain soil fertility at, or where possible improve soil fertility to, a level that ensures optimal and sustained yield.	Records of pesticides use (including active ingredients used and their LD50, area treated, amount of active ingredients applied per ha and number of applications) are provided. Mill water use per tonne of FFB is monitored and recorded. GHG emissions are identified and assessed for the unit of certification. Plans to reduce or minimise them are implemented, monitored through the Palm GHG calculator and publicly reported. Records of fertiliser inputs are maintained.	No No Yes No
4C v4.0 (2020)	Water use efficiency is improved	Water use is documented (not applicable to smallholders)	No
RTRS 4.0	Fossil fuel use is recorded	Total direct fossil fuel use over time is recorded,	No

(2022)	Plan for ensuring preservation of native vegetation and wildlife requires to be implemented. This has monitoring criteria with performance metrics	and its volume per hectare and per unit of product for all activities related to soy production is monitored. See Anne 5 Table 1 of the RTRS standard page 48 for examples of indicators that growers might choose to include in their plan. These include canopy cover (%) or distance to nearest patch of natural vegetation (m or km).	No
Protected Harvest Citrus Standard v 2.0 (2019)	Nutrient Application - Fertigation System Design	If fertigation is used, a written record is maintained of measurement of length of time for materials to move from injection site to the beginning of furthest lateral and from beginning to end of last lateral line.	No
	Irrigation & Water Management - Water Usage Tracking	The total amount of water applied annually for irrigation is recorded and tracked for this production block in order to improve water stewardship and measure effects of water management BMPs on water use.	No
	Energy Management - Energy Use Tracking	The total amount of energy used annually is documented and tracked by source (e.g., electricity, diesel) to measure production performance and is used to assess effects of energy BMPs on energy use.	No
	Energy Management - Stationary Motors - Electrical Pump Efficiency	Electrical pump efficiencies are measured and necessary adjustments to improve efficiencies have been completed within the last two years.	No

Protected Harvest Bloomcheck standard v2.0 (2019)	Pesticide management	Records of pesticide usage, including product name and application date, site, and rate are maintained.	No
	Water management - Pumping Plant Efficiency	If a pumping plant is used, pumping plant efficiency is measured at least every three years and adjustments are made if efficiency is below 50%.	No
	Water use – production	The total amount of water applied annually for irrigation for the entire operation was recorded and tracked to measure and manage water stewardship on the farm and measure effects of water management BMPs on water use.	No
	Water use efficiency	Measurements from weather stations, Soil/substrate moisture depletion measured directly using weight measures for potted plants, tensiometers for in ground plants or other soil-based devices, direct measure of plant stress using stress bombs, radiation measurements	No
	Energy management – energy use	The total amount of energy used annually was documented and tracked by source (e.g., electricity, diesel) to measure production performance and is used to assess effects of BMPs on energy use.	No
	Energy management - Energy Use Efficiency: Stationary Motors	Electrical pump efficiencies were measured and necessary adjustments to improve efficiencies have been completed within the last two years.	No

	Energy Use Efficiency: Postharvest & Cold Storage	Total energy used in cooling and storage was determined annually and tracked over time to monitor the efficiency of cooling equipment and determine when maintenance is required.	No
	Packaging material	The total amount of packaging material used annually in shipments from the production facility was known, recorded, and tracked to optimize use of packing material.	No
		The amount of recycled packaging material used annually in shipments from the production facility was known, recorded, and tracked to optimize use of packing material.	No
Protected Harvest Lodi standard v 4.0 (2022)	Energy management	All fuel and electricity use for the farming operation are tracked.	No
	Manufactured or mined nitrogen application	No more than 10 units of N are applied per application and never when the vine is dormant	No
	Water budget for mature vines	The amount of water used by the vines on a weekly basis is estimated and recorded (cumulative ETc, allowable soil moisture depletion, or plant monitoring) AND less than this amount is applied to the vines during the next week	No
	Water Budget for Young Vines	The amount of water used by the vines on a weekly basis is estimated and recorded (cumulative ETc, allowable soil moisture depletion) AND this amount is applied to the vines during the next week	No
SWNZ	Water	Total area irrigated	No

		Enter value: __ ha / m2	
		Total water used for irrigation this season: Enter value: __ L / m3	No
		Total water used for frost protection this season: Enter value: __ L / m3	No
	Fertiliser and pesticide applications	Fertiliser and pesticide applications need to be recorded in Grapelink	No
	Waste	Total waste sent to landfill this season: Enter value: __m3	No
		Amount of grape marc spread on the vineyard(s) this season Enter value: __ m3	No
		Total vineyard area over which grape marc was spread Enter value: __ ha	No
	Climate change	Carbon emissions must be measured either through a verified certification programme like CarbonZero or relevant ISO standard via independent audit. If not, the grower/winery operatr has to submit records of relevant inputs (diesel, petrol, electricity, other). Total amount of diesel / petrol / electricity used on the vineyard(s) OR by the business this season: [Note for electricity use – if a shared irrigation pump is used, it is recommended that electricity use is allocated on a pro rate basis according to	No

		litres pumped. 1. Determine total amount electricity used (i.e., from power statement); 2. Calculate energy use per m3 or L of water pumped (total kWh divided by total water pumped = kWh per m3 or L of water); 3. Multiply kWh per m3 or L of water by total amount of water the vineyard has used (kWh per m3 of water * total m3 or L of water used on the vineyard = estimated total electricity used on the vineyard)] Enter value: ____ L / kWh	
CWSA	Energy use and GHG emissions	Use the SWP Online System metrics tool to add your metrics data and run the “Metrics Analysis” report for a summary report; or use your own tracking system and share with auditor during the audit. Note: Vineyards: measure and record water use and nitrogen applied annually. Wineries: measure and record water use, energy use, and GHGs annually. Verify that metrics were calculated (per acre/ton or case/gallon) via SWP Online Metrics Calculator; other tracking/software system or CWSA Metrics template.	Not mentioned in standard, calculator access not available for non-members, no further information available online on CWSA metrics calculator.
Equalitas	Carbon footprint	Develop a GHG balance/inventory, updated annually.	Yes. ‘The Equalitas calculation of the CF of a product (CFP) is based on the principles and requirements of UNI EN ISO 140641:2019 (Greenhouse gases-Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals) and UNI EN ISO 14067:2018’. (Casolani et al., 2023)

	Water Footprint	Conduct Water footprint	ISO 14046:2014
VI.VA.	Air indicator	Total GHG emissions (direct and indirect across the life cycle of a 0.75 L bottle of wine, or the GHG inventory of the company	Yes. ISO standards used – ISO 14067 TS (Product Carbon footprint) and ISO 14064 – Part 1 (quantification and reduction of GHGs). The LCA approach considers consumption of pesticides, herbicides, organic/inorganic fertilisers, fossil fuels, electricity land use change, and waste transport and treatment.
	Water Indicator	Total volumes of freshwater used in terms of volumes consumed and polluted.	Yes. It assesses impacts across the life cycle of a 0.75 L bottle of wine. Assesses the water volumes consumed during wine grape production and winery operations. Aligned to the guidelines of the Water Footprint Network – sum of green, blue, and grey water.
SWSA	Wastewater management	Estimate the quantity of wastewater generated.	No
		Sample, record, and monitor wastewater quality at regular intervals.	No
	Water abstraction	Abstraction, storage and use of water must be done, measured and recorded according to the DWS General Authorisation as published in Government Notice No. 538 on 2 September 2016 (See IPW webpage or http://www.gov.za/sites/www.gov.za/files/40243_gen538.pdf). • According to legislation, the volume water abstracted from any source must be measured and recorded at the end of each month	No
		Record of all measurements/determinations regarding each vineyards' water requirements, as well as of all applications of water should be kept to prove that sufficient water was given to satisfy requirements, but no more.	No

		Producers must set objectives to improve water use efficiency (WUE) continually. This entails a recorded calculation of Liters water consumed per kilogram of crop produced and where possible, should be calculated separately for each block/cultivar. Records of water balance sheets and classification of water use types, as well as rainfall must be available. An example of how to keep the required records and do the calculation is available via link on the IPW web page.	No
	Energy Use	To calculate carbon emissions and to measure continual improvement of energy usage, the following records are regarded as the most important, to be recorded in the applicable unit as indicated: o Electricity usage (kWh) o Diesel usage (Liters) o Petrol usage (Liters) o Liquid Petroleum Gas (LPG) usage (kg) o Any other fuels (e.g. coal, furnace oil, etc.) (kg or Liters)	No
	Carbon footprint	Fuel and energy consumption recorded and used for CF calculation	No. Climate Fruit and Wine calculator used
	Fertiliser and pesticide application	All fertiliser and pesticide applications need to be recorded	No
Australian Wine Industry Standards of Sustainable Practice for	Fertiliser and soil additive management	Maintain fertiliser and soil additive records	No
	Chemical application	Chemical application records including rate of application and quantity applied	No

Viticulture	Water management	Water use records (mL/ha)	No
Australian Wine Industry Standards of Sustainable Practice for Winery	Water management	Water management plan must include details about water consumption measurement	No
	Wastewater management	Wastewater volume is measured and reviewed annually against the Water Management Program.	No
		Irrigation records are kept for land areas irrigated with untreated wastewater, including volume of water used or duration of irrigation	No
	Energy and fuel efficiency is optimised throughout the production system.	Electricity and fuel consumption is reviewed at least annually, in consideration of improvement strategies for use.	No

Appendix B – Chapter 2

Table B1 Questionnaire for growers

General Information	1) Name: 2) Age Group: <30 30-40 40-50 50-60 >60 3) Location of farm: 4) Size of area planted with apples (ha): 5) Annual avocado production (2018; tonnes): 6) Type of avocado produced (2018; cultivar): 7) Are your avocados grown: Conventionally Organically Mix 8) How much of your avocados are grown organically (2018): 9) Where do you send your avocados for packaging?
Current mandatory (or de facto mandatory) environmental initiatives/programmes/certification schemes	1) Do you engage in any voluntary environmental initiatives on your farm? 2) Describe these initiatives. How do they work? 3) Why do you have these initiatives in place? (What is your main motivation/driver?) 4) Are these initiatives time-intensive? 5) Are these initiatives cost-intensive? 6) What kind of benefits do these initiatives have – Environmental? Social? Economic? Describe. 7) Do you think these benefits are significant when compared with the time and money invested in these initiatives? 8) What are the main challenges faced with implementing this programme? 9) Is the IPM / IFP programme mandatory? How does it work? 10) Is your farm/s covered under any mandatory or de facto mandatory environmental certification scheme or programme currently? 11) Is it mandatory or voluntary? If mandatory, who requires it? 12) Is it nationally/internationally recognized? 13) Why do you engage in this certification programme? (What is your main motivation/driver?) 14) How does this scheme work? 15) Who conducts the audits? 16) How often must the audits be conducted for you to continue to be certified? 17) Do you think the auditing process is expensive? 18) How much does the auditing process cost you annually? 19) Is the auditing process time-intensive? How long does an audit take? 20) What benefits does this scheme/s have? (Environmental? Social? Economic?)

	21) What are the main challenges you face with this scheme? 22) In your opinion, do the costs involved in complying with the scheme's standards outweigh the benefits of implementing the scheme?
Potential for a new VSS-based environmental certification scheme	1) Do you feel there is potential for an environmental certification programme for the New Zealand avocado sector, for avocado meant for export? Yes No If you answered yes, move on to question 2. If you answered no, please state your reasons for it. 2) What would be the benefits of such a scheme? 3) What would be the challenges and obstacles facing the implementation of such a scheme? 4) Of these challenges, which are the three most important ones? 5) In particular, what are your thoughts on the financial costs, bureaucratic hurdles and time-intensive efforts involved in developing, implementing and running such a certification scheme? 6) Would these costs outweigh the price premiums, brand and image enhancement, increased marketability, and actual environmental benefits of the scheme? 7) What factors/circumstances would help a scheme like this be successful? 8) Do you think the scheme would work better on a sector-wide level (avocado sector) or at the national level for the entire horticulture industry, or as part of an international certification scheme? 9) Who do you think would lead an initiative like this? (An industry association like New Zealand Avocado? A leading exporter like Avoco? The New Zealand government?) 10) What about a collaborative effort between industry association, business and government? What would enable such a multi-stakeholder scheme to be successful? 11) What other stakeholders might be included in the development of such a scheme?

Table B2 Questionnaire for downstream stakeholders (orchard managers, packers, exporters, industry association)

General information	1) Name: 2) Company/Organization: 3) What does your company do: 4) Designation and Job Profile: 5) Experience in the avocado sector? 6) Where do you sell your avocados? Export and/or Domestically? 7) How much do you export and how much do you sell domestically (tonnes/year, 2018): 8) Of your total exports, what is the breakdown of each variety (tonnes/year, 2018):

	9) Of your total exports, how much is organic (tonnes/year, 2018): 10) As a post-harvest operator, do you lease/manage orchards to secure your fruit supply?
Current mandatory (or de facto mandatory) environmental initiatives/programmes/certification schemes	1) Are your avocado packaging and supply operations covered under any environmental certification scheme currently? 2) Is it mandatory or voluntary? If mandatory, who requires it? 3) Is it nationally/internationally recognized? 4) Why do you engage in this certification programme? (What is your main motivation/driver?) 5) How does this scheme work? 6) Who conducts the audits? 7) How often must the audits be conducted for you to continue to be certified? 8) Do you think the auditing process is expensive? 9) How much does the auditing process cost you annually? 10) Is the auditing process time-intensive? How long does it take? 11) Does this scheme/s have any benefits? What kind of benefits are they? (Environmental? Social? Economic?)
Potential for a new VSS-based environmental certification scheme	1) Do you feel there is potential for an environmental certification programme for the New Zealand avocado sector, for avocados meant for export? Yes No If you answered yes, move on to question 2. If you answered no, please state your reasons for it. 2) What would be the benefits of such a scheme? 3) What would be the challenges and obstacles facing the implementation of such a scheme? Of these, what are the three most significant ones? 4) In particular, what are your thoughts on the financial costs, bureaucratic hurdles and time-intensive efforts involved in developing, implementing and running such a certification scheme? 5) Would these costs outweigh the price premiums, brand and image enhancement, increased marketability, and actual environmental benefits of the scheme? 6) What factors/circumstances would help a scheme like this be successful? 7) Do you think the scheme would work better on a sector-wide level (avocado sector) or at the national level for the entire horticulture industry or as part of an international certification scheme? 8) Who do you think would lead an initiative like this? (The industry association New Zealand Avocado? Or an individual company/companies? Or the New Zealand government?) 9) What about a collaborative effort between the industry association, companies and the New Zealand government – what would enable such a multi-stakeholder certification scheme to be successful? 10) What other stakeholders might be included in the development of such an initiative?

Appendix C – Chapter 3

This section includes:

- Questionnaires sent to growers
- List of avocado-related LCA literature identified
- Fertiliser sources of origin and transport distances
- Primary input data for agrichemicals, fertilisers, water, fuel, and electricity; regional yields (kg/ha)
- Comparison of N₂O and CO₂ emissions using factors from two different sources

Note: Table C9 is included as an image due to space restrictions.

Life cycle assessment questionnaire for growers – short version

1 General orchard data

Name of person completing this survey												
PPIN												
Physical address of orchard												
Period of data collection	1 November 2018 to 31 October 2019											
Total area of orchard (ha)												
How many blocks in the orchard?												
Block Number												
Estimated age of each block (years)												
Area of each block												
Area planted in avocados for each block (ha)												
Number of trees on each block												
Are the avocado trees mature and in full production? (Y/N)												
What else do you grow/graze on your orchard? Please provide details (e.g. ha planted in each type of crop or livestock)												

2 Production data

NZ Avocado have provided us with the data for the quantities sent to the packhouse for exports. For that year, did you also sell some **produce locally** that is not included in the NZ Avocado figures? How much roughly in **kilograms**.

.....

3 Fuel and electricity use

3.1 Fuel use

For the given period **1 November 2018 – 31 October 2019** please state the total amount of fuel used on your avocado orchard:

Diesel: Does this **include** fuel use for **irrigation**? **YES / NO**

Does this include fuel use for residences and/or non-commercial activity (eg personal cars)? **YES / NO**

Petrol: Does this **include** fuel use for **irrigation**? **YES / NO**

Does this include fuel use for residences and/or non-commercial activity (eg personal cars)? **YES / NO**

Any other fuel? Does this **include** fuel use for **irrigation**? **YES / NO**

Does this include fuel use for residences and/or non-commercial activity (eg personal cars)? **YES / NO**

If **YES** for any activities, ask roughly **what % is used for the other activities** and make note in table below

Fuel type	Other use	%s used

How many **tractors** do you own and what size are they (horsepower)?
.....

3.2 Electricity use

For the given time period **1 November 2018 – 31 October 2019** please state the total amount of electricity used for the avocado orchard:

kWh

Roughly **what %** is used for different activities?

Activity (e.g. irrigation, shed power use)	% used

4 Contractors

What activities are undertaken by contractors on your orchard?

Activity (mowing, spraying, fertilising, mulching/chipping, shelterbelt trimming, pruning, harvesting etc)	Fuel type used	Number of hours	Do they fill vehicles/equipment with <u>your fuel</u> whilst on the orchard? If yes , specify type of fuel below

5 Water use

For the time period **1 November 2018 to 31 October 2019**:

How much water was used over this period (in litres or m³)?

What is the **source** of your water (river, town supply, bore...)?

If you have a **water pump** on site:

What is energy source for it (electric, diesel, petrol, natural gas)?

Size of pump (kW if electric, horsepower (HP) if diesel etc.)

How many hours did you operate it in that year (roughly)?

How much water comes out of pump per hour (volume flow rate)?

6 Fertiliser use

For the time period **1 November 2018 to 31 October 2019**, see attached print out of your **fertiliser diary**. Please confirm if right or add/delete items if wrong. [Note: if amounts are per tree, then make sure you have the number of trees per block and size of blocks at start of questionnaire.]

7 Agrichemical use

For the time period **1 November 2018 to 31 October 2019**, see attached print out of your **spray diary**. Please confirm if right or add/delete items if wrong. [Note: check if we need to add herbicides e.g. glyphosate, to list.]

Life cycle assessment questionnaire for growers – detailed version

Thank you for agreeing to participate in this important survey to measure the carbon footprint of the avocado industry in New Zealand. Please fill in the questionnaire with as much detail as possible. Be assured that all answers you provide will be kept confidential.

1 General orchard data

Name of person completing this survey	
PPIN	
Physical address of orchard	
Period of data collection	1 November 2018 to 31 October 2019
Total area of orchard (ha)	
How many blocks in the	

orchard?												
Block Number												
Estimated age of each block (years)												
Area of each block												
Area planted in avocados for each block (ha)												
Number of trees on each block												
Are the avocado trees mature and in full production? (Y/N)												
What else do you grow/graze on your orchard? Please provide details (e.g. ha planted in each type of crop or livestock)												
What was the orchard's previous land use?												

2 Production data

Year	Volume sold direct by the grower locally/distributed (kgs)* (A)	Amount sent to packhouse (kgs) (see attached Industry production records as a reference) (B)	Amount produced (kgs) (A+B)
1 June 2016 – 31 May 2017			
1 June 2017 – 31 May 2018			
1 June 2018 – 31 May 2019			
1 June 2019 – 31 May 2020			

*NZ Avocado have provided us with the data for the quantities sent to the packhouse for exports. If some quantity of the produce is **sold locally by the grower themselves**, we need that data as well.

3 Irrigation

Do you irrigate your orchard? Yes No

Is the orchard irrigated entirely or partially? Details (drip or sprinkler irrigation etc.). **If partially irrigated, please mention area of orchard (or % of total orchard area) that is irrigated.**

Do you use your irrigation system **only for water** or also for fertigation/pesticide application and/or frost protection? Please provide details of frost protection if applicable (method, machinery used etc.).

4 Fuel and electricity use

4.1 Fuel use (total)

For the given period **1 November 2018 - 31 October 2019** please state the total amount of fuel used on your avocado orchard*

Diesel: _____ litres

Petrol: _____ litres

*List the total volume of petrol and diesel that you can attribute to the running of equipment, machinery, vehicles and irrigation/fertigation pumps used on the avocado orchard for the given time period. If irrigation/fertigation pumps are fuel-powered, please include pump details in table in Section 5 (Water Use).

4.2 Fuel use by Growers

On-orchard activity *	Machinery used for this activity Please state the number and type of machinery (e.g. mower, hydralada, quad, ATV etc.) and any other relevant details **see note below	Type of fuel used (diesel/petrol/electricity)	Total hours machinery/vehicles were used in this period	Rate of fuel used (L/per hour of use of machinery)** see note below
Mowing				
Spraying				
Fertilising				
Mulching/chipping				
Shelter belt trimming				
Pruning				
Harvesting				
Others				

* Please Do Not Include data (activity and hours of use) for 'non-orchard activities' (like mowing home lawn etc.)

** Fuel consumption/use can be calculated based on the strength of the engine (Hp), or whether the mower is two stroke or four-stroke etc. So, if you cannot provide fuel use rate (L/hour or L/km), please provide as much detail about the machinery (including brand name), engine power etc., that can help us calculate fuel use rate.

4.3 Fuel Use by Contractors

On-orchard* Activity	Machinery used for this activity Please state the number and type of machinery (e.g. mower; hydalada, helicopter, quad, ATV etc.) and any other relevant details ** see note below	Does the machinery belong to the grower or contractor?	Type of fuel used (diesel/petrol/electricity)	Total hours machinery was used in this period; Total kms vehicles were used in this period	Rate of fuel used (L/per hour of use of machinery)** see note below
Mowing					
Spraying					
Fertilising					
Mulching/chipping					
Shelter belt trimming					
Pruning					
Harvesting					
Others					

* Please Do Not Include data (activity and hours of use) for 'non-orchard activities' (like mowing home lawn etc.)

** Fuel consumption/use can be calculated based on the strength of the engine (Hp), or whether the mower is two stroke or four-stroke etc. So, if you cannot provide fuel use rate (L/hour), please provide as much detail about the machinery (including brand name), engine power etc., that can help us calculate fuel use rate.

4.4 Fuel use (Off-orchard transportation)

1 Who do you pack with?

2 From the **1 June 2016 to 31 May 2020**, did you **transport your fruit yourselves** to the packhouse? (Y/N)

If yes:

Year	What weight of fruit did you transport? (kgs)	What kind of vehicle did you use (e.g. small or large truck)?	Was the vehicle diesel or petrol fuelled?	How many return trips did you make to the packhouse?
1 June 2016 – 31 May 2017				
1 June 2017 – 31 May 2018				
1 June 2018 – 31 May 2019				
1 June 2019 – 31 May 2020				

If no:

Year	What kind of vehicle did the packhouse use (e.g. small or large truck)?	How many return trips did the packhouse make?
1 June 2016 – 31 May 2017		
1 June 2017 – 31 May 2018		
1 June 2018 – 31 May 2019		
1 June 2019 – 31 May 2020		

3 Please provide details of **any transport activities** not covered in the question above, but **related to orchard activities** (e.g. personal transport of fruit to local farmers market or getting supplies for the orchard):

4.5 Fuel use (other)

For the given time period **1 November 2018 – 31 October 2019**, please complete the table below for any other fuel use that is not included in Sections 4.2, 4.3 and 4.4.

Activity	Fuel type (e.g. diesel, petrol, lubricants, oil,	Litres used (L)	Estimated amount used for avocado production (ratio or percent

	grease)		contribution)

Electricity use (total)

1. For the given time period **1 November 2018 – 31 October 2019** please state the total amount of electricity used for the avocado orchard

_____ kWh

2. If you are unable to answer the question above, please fill in the table below for each orchard-related activity that uses electricity

Activity (e.g. irrigation, shed power use)	Electrical component	Hours of use across a year (hours)
Irrigation	Electric motor 2kw	40 hours

5 Water use

For the time period **1 November 2018 to 31 October 2019**, please state approximate amounts of water used for different activities.

Activity (e.g. spraying, irrigation, diluting fertilisers)	Amount (L) and source of water			Details of motorised pumps for irrigation/fertigation/frost protection								
	Surface water (e.g. river, streams, ponds)	Town supply	Ground water (Bore)	No. of pumps	Size/type /brand name of each pump / motor	Fuel/electricity or solar powered	If electricity-powered, kW power?	If fuel-powered, then what is the type of fuel (petrol, diesel, natural gas)?	If fuel-powered, what is the rate of fuel use of the pump (L/hour)*	Mass Flow Rate of the pump (also known as pump capacity)**	Pump Efficiency (%)	Run time over a year (hours)***

* If this detail is not available, please mention the brand of pump and other details so the rate can be calculated. ** amount of water that flows through the pump in a given unit of time (L/second, L/minute or L/hour). ***Please only mention the actual run time in hours (the time for which the motor worked to pump water into the irrigation system) instead of overall duration of irrigation (like 5 months)

6 Fertiliser use

For the time period **1 November 2018 to 31 October 2019**, please state quantity of fertiliser and nutritional inputs applied to your avocado trees (**see attached print out of your fertiliser diary if applicable for reference**). Use the fertiliser diary to complete the table below and additionally, include other fertiliser inputs that were not included in the fertiliser diary.

It is important that **ALL** fields are completed. Please **DO NOT** input 'per tree' in the rate column as the 'kg/ha' or L/ha input is required.*

Product**	Amount applied (kg/ha or L/ha)
Notes:	

* Only **IF** per hectare application data is unavailable, please mention application per tree (in which case, please ensure you have provided data for number of trees in each block in the first section of this questionnaire)

** Please state type and source of compost and please mention **brand names** of all fertilisers used

7 Agrichemical use

Please provide details of all agrichemical quantities used (in kg of active ingredient (AI)). **Please see attached spray diary records; if they are correct you do not need to fill in the tables below.**

	Name of chemical(s) (product brand name)	Quantity of Active Ingredient (total kg or kg AI/ha – please specify) if applicable
Pesticides (fungicides and insecticides)	See attached spray diary report for reference If records are complete and correct , please initial here _____	
Herbicides (including weed killers like Roundup)		
Off label agrichemicals		
Others		

Notes:		

8 Other capital equipment used on orchard

8.1 Irrigation equipment

	Material (please state if PVC, LDPE, MDPE or type of metal)	Diameter (mm)	Length (m)	Quantity replaced (m)	Frequency of replacement (years)
Plastic pipes					
Sprinklers					
Pumps					
Other					
Notes:					

Table C1 An overview of the system boundaries and climate change impact scores reported in avocado-related studies internationally

Citation	Type of resource	Products Assessed	Area of Avocado Production	System boundaries	Functional Unit (FU)	Impact Categories Included
D'abbadie & Akbari (2023)	Report	Avocados	Australia	Orchard to domestic market	1 kg avocado and 1 ha of worked orchard	GHG emissions in CO ₂ eq.
Esteve-Llorens et al. (2022)	Peer- reviewed Journal Paper	Avocados and Asparagus	Peru	Orchard to port of export	1 kg avocado	Water footprint – quantitative (water scarcity using AWARE) and qualitative (eutrophication, and freshwater ecotoxicity); Carbon footprint
Solarte-Toro et al. (2022)	Peer-reviewed Journal paper	Avocados (Creole)	Colombia	Orchard stage	1 kg Creole avocado	Carbon and water footprint
Bendotti Avocado (2021)	Public Disclosure Statement	Avocados	Australia	Orchard to domestic/international markets	1 kg avocados	Carbon footprint
Carbon Neutral Avocados (2021)	Public Disclosure Statement	Avocados	Australia	Orchard to domestic/international markets	1 kg avocados	Carbon footprint
Frankowska et al. (2019)	Peer-reviewed Journal Paper	21 types of fruit and 46 fresh and processed products, including avocados	Multiple (Peru, Chile, Israel, South Africa, Spain)	Orchard to consumer	Product level: 1 kg of fresh and processed fruits; and National level: annual consumption of all fruits in the UK	19 impacts including climate change, land use, eutrophication, acidification, toxicity, primary energy demand, and water footprint
Hadijan et al. (2019)	Student Report	Avocado, banana, pineapple	Mexico	Orchard to international market	1 kg fruit	Agricultural land occupation, climate change, natural land

						transformation and water depletion
Bell et al. (2018)	Peer-reviewed Journal Paper	Strawberry, lemon, celery, and avocado	California	Orchard stage	1 kg crop delivered to farmgate	Energy use and GHG emissions
Astier et al. (2014)	Peer-reviewed Journal Paper	Avocados	Central Mexico	Orchard stage	1 ha worked orchard	Energy use and Carbon footprint
Graefe et al. (2013)	Peer-reviewed Journal Paper	Eight crops, including avocados	Colombia	Orchard Stage	1 tonne of crop and 1 ha worked orchard	Energy use and GHG emissions
Bartl et al. (2012)	Peer-reviewed Journal Paper	8 crops including avocados	Peru	Orchard stage	1 kg fruit and 1 ha worked orchard	Climate change, eutrophication, acidification, and human toxicity potential
Stoessel et al. (2012)	Peer-reviewed Journal Paper	34 crops, including avocados	Multiple (Chile, Israel, Peru, Spain, South Africa)	Orchard to point-of-sale	1 kg product at point of sale	Climate change and water stress
Audsley et al. (2009)	Report	Multiple	Multiple (Europe and Global)	Orchard to regional distribution centre	1 kg crops	GHG emissions in CO ₂ eq.

Table C2 Commonly used insecticide products (and their associated AI concentrations) on sampled avocado orchards in New Zealand

Product	AI concentration	Concentration (%)
Verdex 18 EC	18g/L abamectin	1.8
Success Naturalyte	120g/L Spinosad	12
Sparta	120g/L Spinetoram	12
Prodigy	240g/L methoxyfenozide	24
Proclaim	50g/kg Enamectin Benzoate	5
Paramite	110g/L etoxazole	11
Mit e mec	9.3g/L milbemectin	0.93
Lorsban	500g/L chlorpyrifos	50
Invert EW	18g/L abamectin	1.8
Fyfanon EW	440g/L maldison	44
Entrust SC Naturalyte	240g/L Spinosad	24
Dew 600	600g/L diazinon	60
Avid	18g/L abamectin	1.8
Apostle	18g/L abamectin	1.8
Altacor	350g/Kg chlorantriliprole	35

Table C3 Commonly used Cu-based fungicide products on New Zealand avocado orchards

Product	AI – Chemical Containing Copper	Chemical Formula of AI	Percentage of active ingredient in product (%)
Kocide Opti	Cu as copper hydroxide	Cu (OH) ₂	30
Champ DP			37.5
Copper Hydroxide 300			30
ChampION++			30
Blue Shield DF			85.6
Copper Star			30
Cupric Hydroxide 350 SC			35
Champ WG			50
AG Copp 75	Cu as cuprous oxide	(Cu ₂ O)	75
Nordox 75 WG			75
Copper Oxychloride 800 WP	Cu as Copper Oxychloride	(Cu ₂ (OH) ₃ Cl)	75
Tribase Blue	Cu as Tribasic Copper Sulphate	Cu ₃ H ₂ O ₁₀ S ₂	19

Table C4 Commonly used simple fertilisers on avocado orchards in New Zealand

Generic Name	Product Used (Brand name)	If brand name unavailable, assumed brand name	Main Ingredient	Percentage of Main Ingredient in Product (%)
Ammonium Sulphate	Ravensdown granular ammonium sulphate	Ravensdown	Ammonium Sulphate	100
	Fert Wholesale Direct			
Amino Pro N	Amino Pro N (Hortigro)	Hortigro	Amino acid	88
Apple Cider Vinegar / Vinegar	Vinegar	Vinegar	Acetic Acid	8

Superphosphate	Single Superphosphate (Ravensdown)	Ravensdown	Single Superphosphate	100
Triple Superphosphate	Triple Superphosphate (Ballance)	Ballance	Triple Superphosphate	85
			Phosphate rock	4
Magnesium Oxide	Ravensdown Magnesium Oxide	Ravensdown Magnesium Oxide	Magnesium Oxide	95
Magnesium sulfate / Kieserite	Magnesium sulphate Ravensdown	Balance Kieserite (95%)	Magnesium sulfate	97.5
	Kieserite Ravensdown		Magnesium sulfate	85
	Kieserite Ballance		Magnesium sulfate	95
Magnesium Nitrate	Magnesium Nitrate	Trace It Magnesium	Magnesium Nitrate	70
		Krista Mag (Yara)		99
Sodium Borate / Boron	Yaravita Bortrac 150	Yaravita Bortrac 150	Borate (Sodium)	48
	Boron 15% (Winfield United)			48
	Granubor			48
	Solubor			67.5
	Actibor/Etidot-67/Disodium octaborate			100
	Organibor/Borax pentahydrate			32.2
	Ulexite			48
	Agribor			-

	Borax 47			-
	Biomin Boron			48
	Borate 46_ravensdown	Borate 46_ravensdown	Borate (Sodium)	47
Sodium Calcium Borate	Balance Boronate	Ballance Boronate	Sodium Borate	100
Sodium Calcium Borate	Nutrimax Boron 15%	Balance Nutrimax Boron		90
Boric Acid Optibor	Optibor	Optibor	Boric Acid	99
Calcium Borate	Borate 46_ravensdown	Ravensdown Borate 46	Borate (Calcium)	47
Zinc Oxide	Yaravita Zintrac	Yaravita Zintrac	Zinc Oxide	65
CAN / Calcium ammonium nitrate	Yarabela CAN /Ravensdown CAN	Yarabela CAN	CAN	100
Agricultural Copper	Copper sulphate Ravensdown	Copper Sulphate Ravensdown	Copper Sulfate	99
Agriboost	Yates agriboost Granules	Yates Agriboost	Compost	100
Potassium Sulphate or Sulfate of Potash	Yates sulfate of Potash, Balance Sulfate of Potash, Campbell's Solu-K	Ballance Sulfate of Potash	Potassium Sulfate	95
	Ravensdown potassium sulphate		Potassium sulfate	100
Copper Sulfate	Ravensdown Copper Sulfate	Ravensdown Copper Sulfate	Copper sulfate	99
Zinc Sulfate	Biomin Zinc, Ravensdown zinc	Ravensdown Zinc Sulfate	Zinc sulfate monohydrate	99

	sulfate monohydrate, Trace it Zinc			
Sulphur Bentonite	Sulphur 90 (Ravensdown)	Sulphur 90 (Ravensdown)	Sulfur Bentonite Clay	90 10
Calcium 175	Grochem Calcium 175	Grochem Calcium 175	Calcium Chloride	47
Calcium Nitrate	Encal (Grochem)		Calcium Nitrate	65
Potassium Nitrate	Unika Plus, Ballance	Unika Plus, Ballance	Potassium Nitrate	85
Monoammonium Phosphate	MAP, Ravensdown	MAP, Ravensdown	Monoammonium phosphate (also known as ammonium dihydrogen phosphate)	100
Diammonium phosphate	DAP (Ravensdown or Balance)	Ravensdown Balance	DAP (also known as diammonium dihydrogen phosphate)	100 90
Monopotassium Phosphate	MKP Krista, Yara	MKP Krista, Yara	Mono potassium phosphate or Potassium dihydrogenorthophosphate	100
Monocalcium phosphate / MCP, Calcium Phosphate Monobasic Acid, Calcium phosphate, Calcium acid phosphate Calcium biphosphate, Calcium superphosphate, & Monobasic calcium phosphate	Monocalcium phosphate (main ingredient of SSP)	Pestell monocalcium phosphate	Monocalcium phosphate Dicalcium phosphate	60 29
Ammonium nitrate	Ravensdown	Ravensdown	Ammonium nitrate	25

	Nitrophoska	Nitrophoska		
Traceit Manganese	Traceit Manganese / Manganese Nitrate	Grochem Traceit Manganese	Manganese Nitrate	50
Urea (regular)	Ravensdown	Ravensdown	Urea	100
Low Biuret Urea	Ravensdown			99
Urea coated with urease inhibitor	Ravensdown / Ballance (Sustain)			99
Lime (Soil Conditioner)	Ravensdown Aglime	Ravensdown Aglime	Calcium Carbonate as lime	100
	Ravensdown Fine Lime			
	Ravensdown			
Gypsum (Soil Conditioner)	Ravensdown Gypsum	Ravensdown Gypsum	Calcium Sulphate	100
Dolomite (Soil Conditioner)	Ravensdown dolomite	Ravensdown Dolomite	Dolomite	100
	Ballance Dolomite			

Table C5 Commonly used NPK fertiliser on avocado orchards in New Zealand

Generic Name	Product Used (Brand name)	If brand name unavailable, assumed brand name	Main Ingredient	Percentage of Main Ingredient in Product (%)
NPK Fertiliser	Nitrosol (Rainbow & Brown)		Nitrogen	11
			Phosphorous	5
			Potassium	7
NPK Fertiliser	Novatec Premium		Nitrogen	15
			Phosphorous	1.3
			Potassium	16.6

NPK Fertiliser	Novatec Classic / Balukorn Classic		Nitrogen	12
			Phosphorous	8
			Potassium	16
NPK Fertiliser	Special Mix NPK Fert		Nitrogen	11
			Phosphorous	4
			Potassium	14
Avocado Mix Blend (NPK 5.6-4.5-10.7)	Avocado Mix Blend (NPK 5.6-4.5-10.7)		Nitrogen	5.6
			Phosphorous	4.5
			Potassium	10.7
Finish it / Finish It Plus (NPK 6-6-30)	Finish it / Finish It Plus (NPK 6-6-30)		Nitrogen	6
			Phosphorous	6
			Potassium	30
Rustica Blue Extra (NPK 12-5-14)	Rustica Blue Extra		Nitrogen	12
			Phosphorous	5
			Potassium	14
NPK Fertiliser (12-5-15)	Hortigro / other		Nitrogen	12
			Phosphorous	5
			Potassium	15

HG Avo (NPK 4-4-16)	Agri Technovation		Nitrogen	4
			Phosphorous	4
			Potassium	16
PK fertiliser	Yaratera Super FK 30		Phosphorous	8
			Potassium	5
Foscheck 400 / Foscheck/ Phosgard 400	Foscheck 400 / Phosgard 400	Foscheck	Phosphorous	11
			Potassium	16
Nitrosol peptone amino	Nitrosol peptone amino	-	Nitrogen	15
Nitrosol Original	Nitrosol Original	Nitrosol original	Nitrogen	8
			Phosphorous	3
			Potassium	6
Avo K	Avo K (Grochem)	Avo K	Nitrogen	10
			Phosphorous	5
			Potassium	14
Fertiboost	Fertiboost (Pacific Ag)	Fertiboost	Nitrogen	10
			Phosphorous	4
			Potassium	8
Delta Spray	Delta Spray	Delta Spray	Nitrogen	15
			Phosphorous	5

			Potassium	30
Smartfert	Smartfert	Smartfert	Nitrogen	17
			Phosphorous	2
			Potassium	10.5
Plasma Hort	Plasma Hort	Plasma Hort	Nitrogen	8
			Phosphorous	3
			Potassium	4

Table C6 Commonly use complex fertiliser on avocado orchards in New Zealand

Generic Name	Product Used (Brand Name)	If brand name unavailable, assumed brand name	Main Ingredients	Percentage of Main Ingredient in Product (%)
Autumn mix	PhaSedN from Ballance	PhaSedN from Ballance	Urea	50
			Sulfur	30
			Limestone	18
Avocado Mix	Ravensdown Avocado Mix + TE	Ravensdown Avocado Mix + TE	Ammonium nitrate	20
Avocado Regular			Magnesium sulfate (from keiserite)	10.2
Avo Base			Potassium sulphate	6
Avo Cuttings Mix			Sodium Borate	0.94
Avo Mix Extra Boron			Zinc sulphate	1.96
Avo Mix + TE				
Avocado young trre mix + TE				
Avogain	Advance Avogain	Advance Avogain	Potassium Sulphate	15

	(Ballance)	(Ballance)	Ammonium nitrate	15
			Magnesium sulphate	15
			Potassium Nitrate	15
			Ammonium sulphate	10
			Mono-ammonium phosphate	5
			Calcium phosphate dibasic (or as decided, referred to as mono calcium phosphate)	5
			Diammonium phosphate	5
			Mono potassium phosphate	5
			Calcium fluoride	5
			Zinc sulfate	0.5
			Sodium borate	1
Yaramila Complex	Yara Mila Complex Ballance	Yara Mila Complex Ballance	Potassium Sulphate	23
			Ammonium nitrate	17.5
			Potassium Nitrate	14
			Ammonium sulphate	11.5
			Mono ammonium phosphate	6
			Mono Calcium phosphate	6
			Mono Potassium Phosphate	6
Yara Mila Grower	Yara Mila Grower Ballance	Yara Mila Grower Ballance	Potassium Sulphate	42.5
			Ammonium nitrate	30
			Magnesium sulphate	8.5
			Mono ammonium phosphate	6
			Gypsum	4

			Mono Potassium phosphate	2.5
			Ammonium sulphate	2.5
			Diammonium phosphate (DAP)	2.5
Yara Mila 8-11-20	Yara Mila 8-11-20 Ballance	Yara Mila 8-11-20 Balance	Mono ammonium phosphate	27.5
			Potassium sulfate	22.5
			Potassium chloride	17.5
			Diammonium phosphate	8.5
			Ammonium sulfate	6
			Mono potassium phosphate	4
			Potassium nitrate	2.5
			Ammonium nitrate	2.5
			Ammonium chloride	1.5
Nitrabor	Yara Live Nitrabor Balance	Yara Live Nitrabor Ballance	CAN	95
			Sodium borate	2.5
Trace it Boron	Grochem Trace it Boron	Grochem Traceit Boron	Boric Acid	9
			Copper sulfate	2
			Zinc Sulfate	11
			Manganese sulfate	10
Blaukorn Classic	Blaukorn Classic	Blaukorn Classic	Ammonium Nitrate	27
			Sodium Borate	0.2
			Phosphate	8
			Potassium Oxide	16
			Magnesium Oxide	3
			Sulphur	9
Budmate	Agrichem Budmate	Budmate	Lime	50
			Magnesium Carbonate	20
			Urea	10

			Zinc Oxide	5
			Boric Acid	5
Bud-wiser	Bud-wiser	Bud-wiser (grochem)	Boric Acid	28
			Zinc Sulfate	8
Calcium phosphate	Grochem Calphos	Grochem Calphos	Phosphoric acid	20
			Calcium Phosphate	30
Wuxal Boron	Wuxal Boron	Wuxal Boron	Boric Acid	45
			Nitrogen	8
			Phosphorous	4.3
Wuxal Zinc	Wuxal Zinc	Wuxal Zinc	Zinc Sulfate (assumed)	15
			Nitrogen	5
UAN	Urea Ammonium Nitrate	UAN	Urea	41
			Ammonium nitrate	50

Table C7 Assumed fertiliser sources of origin and transport modelling choices

Fertiliser/Soil Conditioner	Assumed Country/Region of Origin	Transport Distances
Lime	Rarewa, Whangarei ⁵⁴	The manufactured lime was modelled for transport to the retailer in Kaitaia (150 km) and forward 50 km to orchards in Pukenui in the Far North (192 kms by truck); to orchards in Whangarei (50 km – no retailer stage modelled); and 360 km to retailers in Tauranga, and forward 50 km to orchards in Tauranga (50 kms).
Dolomite	Collingwood, Tasman	Dolomite transport was modelled across 270 kms from the Collingwood quarry ⁵⁵ to Picton Interislander ferry terminal, 100 km by ferry to Wellington, 500 km to the retailer in Tauranga, 800 km to the retailer in Whangarei and 950 km to the retailer in Kaitaia, and 50 kms to orchards in all three regions from retailers in the respective regions.
Urea	Taranaki ⁵⁶	Urea transport was modelled across a trucked distance of 350 km from Taranaki to a retailer in Tauranga city and forward 50 km to the orchard; 560 km from Taranaki to a retailer in Whangarei city and forward 50 km to the orchard; and 720 km from Taranaki to a retailer in Kaitaia, and forward 50 km to orchards in Pukenui in the Far North.
Single Superphosphate	Phosphate rock from Morocco and smaller quantity from Vietnam. SSP manufactured in New Zealand, therefore local transport was modelled for SSP.	Since 70% of the phosphate rock used in New Zealand comes from the Western Sahara, the transport of that proportion was modelled is modelled from the manufacturing plant/quarry in the Western Sahara to the Moroccan port of Agadir by truck (640 km); and from Agadir Port to Auckland Port by ship (approximately 19,816 kms). The remaining 30% is sourced from Vietnam (representing South-east Asian sources of phosphate rock). This quantity was modelled for transport over 100 km by truck from quarry to Saigon Port; and from Saigon Port to Auckland port by ship (9,997 kms). The

⁵⁴ Northland has abundant resources of lime (Christies, Thompson & Brathwaite, 2007; Mortimer & Strong, 2014). Thus, for this study, lime production was assumed in Rarewa, Whangarei (Avoca, 2021).

⁵⁵ The Golden Bay Dolomite quarry in Collingwood is New Zealand's only source of commercial dolomite (Golden Bay Dolomite, 2017)

⁵⁶ New Zealand's only urea plant is located at Kapuni in South Taranaki.

		phosphate rock is transported across 215 kms from Auckland port to Mount Maunganui by truck. The formulated superphosphate is then transported 15 kms to a local retailer in Tauranga, and then 50 kms to orchards in Tauranga. For use in Whangarei, formulated superphosphate is transported 360 kms to the retailer in Whangarei city, and then 50 km for use on orchard in Whangarei. For the Far North, the formulated superphosphate is modelled for transport across 515 kms by truck to the retailer in Kaitaia, and forward 50 kms for use on the orchards in Pukenui.
Reactive Phosphate Rock	Phosphate rock from Morocco, followed by local transport of RPR	For Reactive Phosphate Rock (RPR) production, it was modelled for international production (an Ecoinvent Global dataset was used to model production) and then import from Morocco, following the same international transport distances as mentioned above. Local transport was modelled as per all other imported fertilisers - 200 km to regional storage and 100 kms to the orchard.
Agricultural Salt	Mount Maunganui, Tauranga	The formulated agricultural was modelled for transport over 15 kms to a local retailer in Tauranga and then 50 kms to orchards in Tauranga. For use in Whangarei, it was transported 360 kms to the retailer in Whangarei city, and then 50 km for use on the orchard in Whangarei. For the Far North, the product was modelled for transport across 515 kms by truck to the retailer in Kaitaia and forward 50 kms for use on the orchards in Pukenui.
Compost	Local, various	Compost is usually locally available. Therefore, for compost inputs, a shorter transport route was assumed: truck transport to orchard (25 km).
Gypsum	South Australia	Gypsum was assumed to be mined in Lake McDonnell, South Australia, trucked to Port Lincoln (490 km), shipped to Auckland port (3771 km), trucked to regional storage in Auckland (200 km), and then 100 km to the orchard.
All Other Products	Germany	The model thus assumed truck transport from the 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/Kaitaia (average 200 km); and finally truck transport to the orchard from regional storehouse (100 km).

Table C.8 Orchard agrichemical input quantities (kg/ha) for all orchards in the baseline model

Region	Assigned orchard number	<u>Insecticide Use</u>		<u>Herbicide Use (Glyphosate / Glufosinate)</u>		<u>Fungicide Use (Cu-based)</u>		<u>Mineral Oil Use</u>	
		Total Product (kg/ha)	AI quantity (kg/ha)	Total Product (kg/ha)	AI Quantity (kg/ha)	Total Product (kg/ha)	AI Quantity (kg/ha)	Total Product (kg/ha)	AI Quantity (kg/ha)
Mid North	1	7.16	1.36	5.5	1.97	0	0	-	-
Mid North	2	4.6	0.9	5	1.8	4.3	3.2	-	-
Mid North	3	5.43	1.03	-	-	-	-	10.8	8.9
Mid North	4	4.5	0.85	1.6	0.58	8	6.1	-	-
Mid North	5	-	-	-	-	-	-	-	-
Mid North	6	2.1	0.4	-	-	1.7	1.3	-	-
Mid North	7	22.8	4.33	0.4	0.14	-	-	-	-
Mid North	8	6.22	1.2	3.36	1.2	-	-	-	-
Mid North	9	3.27	0.62	12.5	4.5	3.8	3	14.07	10.73
Mid North	10	6.9	1.3	0.65	0.24	-	-	-	-
Mid North	11	3.3	0.62	-	-	25.6	7.8	-	-
Mid North	12	5.1	0.97	4.2	1.5	-	-	-	-
Mid North	13	0.85	0.16	7.4	2.7	0.7	0.52	-	-
Mid North	14	9.85	1.87	4.2	1.5	1.5	1.06	-	-
Bay of Plenty	15	14.9	2.8	-	-	-	-	-	-
Bay of Plenty	16	4.43	0.84	-	-	15	4.6	103.7	85.4
Bay of Plenty	17	96.64	18.36	-	-	19.6	12	-	-

Bay of Plenty	18	293.4	55.7	6	1.75	115.3	35	-	-
Bay of Plenty	19	3.06	0.58	-	-	-	-	-	-
Bay of Plenty	20	36.16	6.87	0.6	0.22	14.6	4.5	51.8	42.7
Bay of Plenty	21	3.9	0.74	1	0.35	12	3.2	21.6	17.82
Bay of Plenty	22	10.5	2	0.6	0.2	26.8	6.6	79.9	65.8
Bay of Plenty	23	4.58	0.87	-	-	-	-	-	-
Bay of Plenty	24	29.11	5.53	-	-	12.9	4	83.2	68.56
Bay of Plenty	25	3.9	0.74	2.7	0.53	10	3.1	-	-
Bay of Plenty	26	9.06	1.72	0.2	0.06	5.1	1.1	21.6	17.8
Bay of Plenty	27	90.11	17.12	1.1	0.4	73.2	54.9	25.9	21.4
Bay of Plenty	28	7.58	1.44	-	-	9	2.7	64.8	53.4
Bay of Plenty	29	8.3	1.58	-	-	0.8	0.3	33.5	27.5
Bay of Plenty	30	4.11	0.78	1.1	0.4	6.8	2.1	64.8	53.4
Bay of Plenty	31	18.2	3.45	-	-	15.2	11.4	97.16	80.07
Bay of Plenty	32	3.74	0.71	1.1	0.4	11.8	3.1	21.6	17.8
Bay of Plenty	33	5.58	1.06	1.1	0.4	7.3	1.7	32.4	26.7
Bay of Plenty	34	7.11	1.35	1.1	0.4	7.3	2.3	25.9	21.37
Bay of Plenty	35	6.85	1.3	1.1	0.4	9.1	2.8	21.6	17.8
Bay of Plenty	36	93.74	17.81	1.1	0.4	73.2	24.4	32.4	26.7
Bay of Plenty	37	14.9	2.83	0.79	0.29	11.3	3.62	45.45	34.9
Bay of Plenty	38	3.85	0.73	-	-	31.5	7	-	-
Far North	39	22.74	4.32	0.4	0.07	-	-	-	-
Far North	40	2.53	0.48	0.23	0.05	-	-	-	-
Far North	41	43.9	8.34	12.4	4.7	5.6	3	32.55	26.8
Far North	42	48.27	9.17	18.97	5.64	150.2	45.1	-	-
Far North	43	142.74	27.12	6.62	2.4	133.7	65.8	87.66	68.75
Far North	44	28.11	5.34	7.25	2.61	19.7	6.1	-	-

[illegible]

Table C9 Fertiliser input quantities (kg/hectare) for all orchards in the baseline model

[illegible]

Table C10 Input Quantities of fuel, water, and electricity on all orchards in the baseline model

Region	Assigned numbers	Fuel, Water and Electricity Use per hectare				
		Diesel Use (L/Ha)	Petrol Use (L/Ha)	Other Fuel (L/Ha)	Water Use (m ³ /Ha)	Electricity Use (kWh/Ha)
Mid North	1	332	280.2	0	276.4	188.4
Mid North	2	288.8	422	0	385.5	100
Mid North	3	428.6	292.9	0	675	0
Mid North	4	100.4	29.8	0.9	259.1	155.8
Mid North	5	481.2	120	10	350	120
Mid North	6	500	186.7	10	3.4	0
Mid North	7	496	0	0	2.3	21
Mid North	8	467.2	200	0	560	112.1
Mid North	9	62.5	136.2	0	251.5	0
Mid North	10	164.7	111.9	2.2	102.1	0
Mid North	11	135.6	122.3	0	27.8	166.7
Mid North	12	91.2	151.7	0	4	0
Mid North	13	110	221.7	0	291.6	32.5
Mid North	14	93.8	192.5	0	9.4	0
Bay of Plenty	15	259.4	114.3	0	14.3	0
Bay of Plenty	16	53.4	223.4	1.4	9.4	0
Bay of Plenty	17	262.1	281.3	4.2	8	0
Bay of Plenty	18	460.4	387.4	6.7	478.3	1507
Bay of Plenty	19	215	100	0	6	0
Bay of Plenty	20	228.4	131	0.1	9.6	0
Bay of Plenty	21	190.5	198.3	0.2	14.3	0
Bay of Plenty	22	170.2	173.5	0	306.4	459.6

Bay of Plenty	23	230.4	187.7	0	18.6	0
Bay of Plenty	24	409	247.1	0	32	0
Bay of Plenty	25	285.6	56.7	0	13.2	0
Bay of Plenty	26	242.6	197.8	0	12.7	0
Bay of Plenty	27	308	367.8	0	13.6	0
Bay of Plenty	28	138	274	0	6	0
Bay of Plenty	29	208.5	426	0	0	2.6
Bay of Plenty	30	242.5	197.8	0	1.8	0
Bay of Plenty	31	324.8	261.4	41.9	30.7	454.6
Bay of Plenty	32	400	220.9	0	7.8	454.5
Bay of Plenty	33	243.9	137.7	0	121.2	0
Bay of Plenty	34	104.4	26.3	0	89.3	170.7
Bay of Plenty	35	271.8	69.7	0	4.1	0
Bay of Plenty	36	242.6	197.9	0	196.9	132.4
Bay of Plenty	37	242.6	197.9	0	89.3	0
Bay of Plenty	38	86.1	71.7	0	569.2	454.5
Far North	39	764.4	84.6	15.9	2526.7	606.6
Far North	40	449.6	49.8	11.9	1855.3	194
Far North	41	527.8	63.7	0.5	1151.3	433.9
Far North	42	247.2	36.8	0	6850.6	6014
Far North	43	460.2	170.9	15.9	282.9	303.8
Far North	44	207.3	166.6	0	3013.7	1656.7
Far North	45	1204.4	505.4	0	44	1607.4
Far North	46	902.2	378.6	0	33	1203.9
Far North	47	623.7	261.7	0	1581.7	2186.9
Far North	48	800.1	335.7	0	3866.8	2618.6
Far North	49	618.7	205.4	0	1224	1682.6

Table C11 Orchard inputs for 'supra-massive' orchards

		Fertiliser (except soil conditioners) (kg/ha)	Total N Input (Kg/ha)	Total P Input (Kg/ha)	Soil Conditioners (kg/ha)			Agrichemicals (kg/ha)				Fuel (L/ha)		Water (m ³ /ha)	Electricity (kWh/ha)
					Lime (excluding CAN)	Dolomite	Gypsum	Insecticides	Herbicides	Fungicides	Mineral Oil	Diesel	Petrol		
a		2081.76	133.5	76.13	1000	0	1000	15.5	17.3	0.3	0	164.7	27.7	458.9	0
b		1184.5	153.55	32.9	485	0	0	0	11.65	0	0	172.3	61.3	579.7	1161.3
c		894.5	136.8	29	485	0	0	3.2	31.75	0	0	159.4	12.8	633.9	1764.8
d		1339	120.8	41.5	0	0	0	4.4	11.65	0	0	144.7	46.5	760.6	1695.5

Table C12 Average baseline yields of the orchards in each of the three studied regions

	<u>Annual yield (kg/ha)</u>
<u>Far North</u>	14723
<u>Mid North</u>	9326
<u>Bay of Plenty</u>	11751

Table C13 Nitrous oxide and carbon dioxide emissions (and climate change impact/kg N as fertiliser) of nitrogen fertilisers in Ministry for the Environment (2020) and EPD International (2019)

	Ministry for the Environment (2020)								EPD International (2019)							
	Direct N ₂ O (per kg N as fertiliser)	Indirect N ₂ O (per kg N as fertiliser)		Total N ₂ O (per kg N as fertiliser)	CO ₂ (per kg N as fertiliser)	N ₂ O (kg CO ₂ eq./kg N as fertiliser)	CO ₂ (kg CO ₂ eq./kg N as fertiliser)	Total GWP (kg CO ₂ eq./kg N as fertiliser)	Direct N ₂ O (per kg N as fertiliser)	Indirect N ₂ O (per kg N as fertiliser)		Total N ₂ O (per kg N as fertiliser)	CO ₂ (per kg N as fertiliser)	N ₂ O (kg CO ₂ eq./kg N as fertiliser)	CO ₂ (kg CO ₂ eq./kg N as fertiliser)	Total GWP (kg CO ₂ eq./kg N as fertiliser)
Urea (no UI*)	0.0093	0.0016	0.0008	0.0117	1.594	3.1005	1.594	4.7	-	-	-	-	-	-	-	-
Urea (UI)	0.0093	0.0009	0.0008	0.011	1.594	2.915	1.594	4.51	-	-	-	-	-	-	-	-
Non urea fertiliser (generic)	0.0157	0.0016	0.0008	0.0181	0	4.7965	0	4.8	-	-	-	-	-	-	-	-
Urea (undifferentiated) (46% N)	-	-	-	-	-	-	-	-	0.016	0.005	0.005	0.026	1.59	6.89	1.59	8.48
Ammonium sulfate (20% N)	-	-	-	-	-	-	-	-	0.016	0.003	0.005	0.024	0	6.36	0	6.36
CAN (27% N)	-	-	-	-	-	-	-	-	0.011	0.003	0.003	0.017	0	4.505	0	4.51
Mono Ammonium Phosphate (12% N)	-	-	-	-	-	-	-	-	0.014	0.004	0.004	0.022	0	5.83	0	5.83
Di Ammonium Phosphate (18% N)	-	-	-	-	-	-	-	-	0.016	0.004	0.004	0.024	0	6.36	0	6.36
Generic mineral N fertilisers with 12% N (e.g. Nitrophoska Extra)	-	-	-	-	-	-	-	-	0.012	0.0016	0.005	0.0186	0	4.929	0	4.93
Generic mineral N fertilisers with 17% N (e.g., Smartfert)	-	-	-	-	-	-	-	-	0.016	0.0016	0.005	0.0226	0	5.989	0	5.99

*UI – coated with urease Inhibitors; non-UI – not coated with urease Inhibitors; undifferentiated – no differentiation between coated and uncoated urea; Green box – value lower than MfE (2020); Orange box – value higher than MfE (2020)

Table C14 Fertiliser application emission factors

Fertiliser emissions - Nitrogen							
Fertilizer Type	Emission Factor for Ammonia (kg NH ₃ -N volatilized per kg of N in fertilizers applied)	Emission factor for direct N ₂ O emission (kg N ₂ O-N emitted per kg of N in fertilizers applied)	Emission factor for direct NO emission (kg NO-N emitted per kg of N in fertilizers applied)	Emission factor for indirect N ₂ O emission (per kg of NH ₃ -N volatilized from fertilizers applied)	Emission factor for indirect N ₂ O emission (per kg of NO ₃ --N lost by leaching/runoff)	Emission factor for NO ₃ - indirect emission (per kg of N in fertilizers applied)	Source
Ammonium Nitrate	0.037	0.008	0.006				PCR Fruits and Nuts (2018)
Anhydrous Ammonia	0.011						
Mono and Di Ammonium Phosphate	0.203	0.009	0.007				
Ammonium Sulfate	0.141	0.01	0.007				
CAN	0.022	0.007	0.006				
Calcium Nitrate	0.009						
Urea	0.243	0.011	0.007				
Other NK and NPK fertiliser	0.037						
Ammonia, direct application		0.009	0.005				
Nitrogen solutions		0.01	0.007				
Other straight N		0.012	0.01				

Compound NK-N		0.009	0.008				
Compound NPK-N		0.008	0.006				
Other NP-N compound		0.009	0.006				
Generic mineral N fertilisers		0.01	0.007	0.01	0.0075	0.3	
Compost*		0.01					IPCC 2006 (N ₂ O emissions from managed soils, and CO ₂ emissions from lime and urea application)
Fertiliser Application Emissions - Phosphorous							
	Leaching of soluble phosphate to ground water (kg/ha)	Run-off of soluble phosphate to surface water (kg/ha)	Erosion of soil particles containing phosphorus to surface water (kg/ha)				Source
Fertiliser	Calculated	Calculated	0.53				PCR Fruits and Nuts (2018)
Fertiliser Application Emissions – Carbon Dioxide							
	Emission factor for urea (kg	Emission factor for lime (kg CO ₂ /kg	Emission factor for dolomite (kg				Source

	CO2/kg Urea applied)	limestone)	CO2/kg dolomite)				
Urea	1.59						Measuring Emissions: A Guide for Organisations: 2020 Detailed Guide – MfE (2020)
Lime		0.44					
Dolomite			0.88				

Table C15 Water use emission factors (AWARE)

<u>Region</u>	<u>AWARE CFs</u>
National, unspecified	9.53
Bay of Plenty	0.51
Northland	1.52

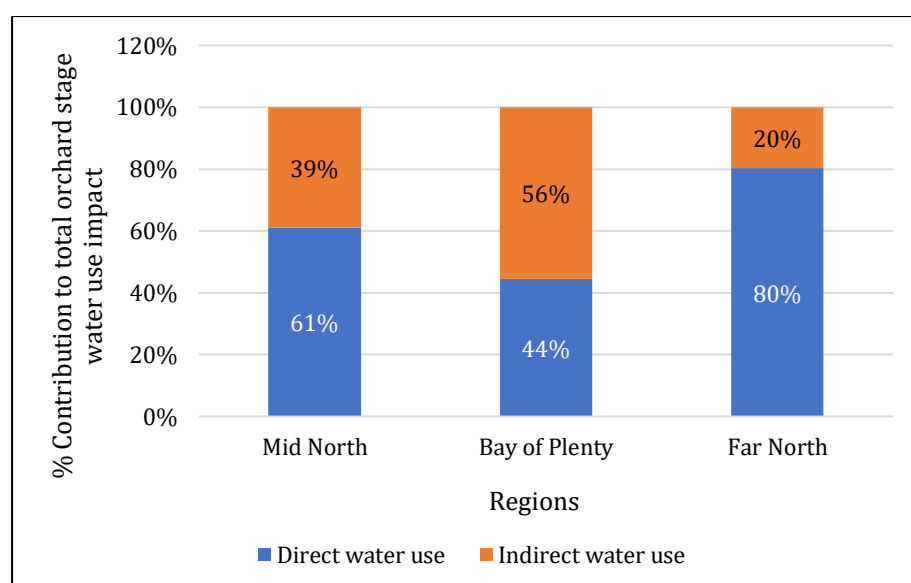


Figure C1 Relative contributions of direct and indirect water use to the total impact score for the orchard stage for the three regions (using the national agricultural CF for water use)

References

- Avoca (2021) Lime. Calcium in our agricultural lime (aglime) neutralises soil acidity for healthier pastures. <https://avocagroup.co.nz/products/lime/> Accessed 15 January 2022
- Bay of Plenty Regional Council (2013). *NERMN Groundwater Monitoring Report*. https://www.boprc.govt.nz/media/470826/nermn-groundwater-monitoring-report_part1.pdf Accessed 17 September 2021
- Christie T, Thompson B, Brathwaite B (2007) Mineral Commodity Report 21 - Limestone, Marble, and Dolomite. <https://www.nzpam.govt.nz/assets/Uploads/doing-business/mineral-potential/limestone.pdf> Accessed 26 July 2021
- Cotton Info (2021) Fundamentals of Energy Use in Water Pumping. <https://cottoninfo.com.au/publications/energy-fundamentals-energy-use-water-pumping> Accessed 26 July 2021
- Del Borghi A, Strazza C, Gallo M, Messineo S, Naso M (2013) Water supply and sustainability: life cycle assessment of water collection, treatment and distribution service. *The International Journal of Life Cycle Assessment* 18:1158-1168
- Golden Bay Dolomite (2017) About Dolomite. <https://dolomite.co.nz/> Accessed 21 February 2021
- Irrigation NZ (2015) Hydraulics and Pumping – Book 10. <https://www.irrigationnz.co.nz/PracticalResources/COP/HydraulicsAndPumping> Accessed 16 February 2021
- Karimi P, Qureshi AS, Bahramloo R, Molden D (2012) Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran. *Agricultural Water Management* 108:52-60
- Mortimer N, Strong DT (2014) New Zealand limestone purity. *New Zealand Journal of Geology and Geophysics* 57(2):209-218
- NASA (National Aeronautics and Space Administration) (2021) Mass Flow Rate. <https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/mass-flow-rate/> Accessed 25 May 2021

Smith P (2015) Is your Diesel Pump Costing you Money? A publication by the Department of Primary Industries, New South Wales Government. Accessed 3 June 2021

Smith K, Liu S (2017) Energy for conventional water supply and wastewater treatment in urban China: A review. *Global Challenges* 1, 1600016 – 1600022

Tidwell VC, Moreland B, Zemlick K (2014) Geographic footprint of electricity use for water services in the western U.S. *Environmental Science & Technology* 48:8897-8904

Appendix D – Chapter 4

This appendix contains:

- Questionnaires sent to packers and exporters
- Assumptions and data choices
- LCI data
- Calculations
- Graph on including business transport at the packhouse stage

Life cycle assessment questionnaire for packers

1 General packhouse data

Name of packhouse					
Name of person completing this survey					
Period chosen for data collection	1 June 2019 to 31 May 2020				
Cooling system - separate or central refrigeration system?					
Type of refrigeration technology					
Number of coolstores					
Size of each coolstore (m ³)					
Number of coolstores used for avocados					
Size of each coolstore used for avocados (m ³)					
Number of days each coolstore is operated for avocados					
Number of coolstores used for other produce					
Size of each coolstore used for other produce (m ³)					
Number of days each coolstore is operated for other produce					
Notes:					

2 Processing

2.1 Total quantity of avocados processed at packhouse

For the time period **1 June 2019 to 31 May 2020**.

Total quantity received (kgs)	Total quantity Class 1 fruit packed and sent for export (kgs)	Total quantity Class 1 fruit packed and sent for domestic distribution and retail (kgs)	Total quantity Class 2 fruit packed and sent for export (kgs)	Total quantity Class 2 and 3 fruit packed and sent for domestic distribution and retail (kgs)	Total quantity of fruit sent for oil processing (kgs)	Total quantity of reject fruit ending up in waste stream (kgs)

Notes:

2.2 Waste fruit

For the time period **1 June 2019 to 31 May 2020**.

Quantity of waste fruit (last column of previous table) (kg)	Quantity given away as feedstock (kg)	Quantity of fruit sent to landfill (kg)	Quantity of fruit sent to compost (kg)
Other method(s) and quantity:			

2.3 Other products

For the time period **1 June 2019 to 31 May 2020** please provide details of products other than avocados handled by the packhouse.

Product	Total quantity (kg)	% volume/area of packhouse dedicated to this product	Length of storage (days, weeks, months)
Notes:			

1. How long was the packhouse closed down between **1 June 2019 to 31 May 2020** (days)?

2. What % of the time the packing line is operating, was dedicated to avocados between **1 June 2019 to 31 May 2020**?

2.4 Packaging

2.4.1 Bins

Bins used for the time period **1 June 2019 to 31 May 2020**.

Item	Name and location of supplier	Material (e.g. timber)	Weight of bin (kg)	How many bins used for avocados are replaced each year?
Wooden bin				
Plastic bin				

2.4.2 Packaging for export fruit

For the time period **1 June 2019 to 31 May 2020** please provide details of all packaging materials used for **one pallet**. Please add any other items not included in this list.

Tray type	Number of trays per pallet	Fruit weight per tray	Percentage split between pallet types (e.g. 80% exported as SL)
Single layer (SL)			
Bulk			

Item	Name and location of supplier	Material (e.g. cardboard, plastic, PET)	Weight (kg)	Waste packaging sent to landfill*	Waste packaging sent to recycling**
Shrink wrap (wrapped around packaging arriving at packhouse)					
Tray - Single layer					
Tray - Bulk					
Strapping (packaging arriving at packhouse and on					

pallets leaving packhouse)					
Liners					
Pocket packs					
Fruit stickers					
Pallet corner boards					
Pallet crown					
Tamawrap					
Pallets					
Lime					
Other					
Notes:					

* Estimate of % wasted in processing line (e.g. 1 box for every 100 boxes used)

**Estimate of % sent to recycling, of total amount wasted (e.g. 1 box (of every 10 boxes wasted) is sent to recycling)

2.4.3 Packaging for local market fruit

For the time period **1 June 2019 to 31 May 2020** please provide details of all packaging materials used for **one pallet**. Please add any other items not included in this list.

Tray type	Number of trays per pallet	Fruit weight per tray	Percentage split between pallet types (e.g. 80% local as Bulk)
Single layer (SL)			
Bulk			

Item	Name and location of supplier	Material (e.g. cardboard, plastic, PET)	Weight (kg)	Waste packaging sent to landfill*	Waste packaging sent to recycling**
Shrink wrap (wrapped around packaging arriving at packhouse)					
Tray - Single layer					
Tray - Bulk					
Strapping (packaging arriving at packhouse and on pallets leaving packhouse)					
Liners					
Pocket packs					
Fruit stickers					
Pallet corner boards					
Pallet crown					
Tamawrap					
Pallets					
Lime					
Other					

Notes:

* Estimate of % wasted in processing line (e.g. 1 box for every 100 boxes used)

**Estimate of % sent to recycling, of total amount wasted (e.g. 1 box (of every 10 boxes wasted) is sent to recycling)

2.4.4. Lime

For the time period **1 June 2019 to 31 May 2020**

Item	Name and location of supplier	Weight used (kg)	Waste lime sent to landfill	Waste packaging sent to landfill	Waste packaging sent to recycling
Lime					

2.5 Refrigerant use

For the time period **1 June 2019 to 31 May 2020**. Please add any additional relevant detail in the notes section.

Type of refrigerant (name of product)	Where is it sourced from? (locally or internationally sourced, name of company)	Total quantity purchased in one year (kg/year)	Total quantity used to charge system in one year (kg/year)	Does this include recharging after accidental losses during the year? (Provide number of accidents and quantities in kg)

Notes:

2.6 Electricity use

For the time period **1 June 2019 to 31 May 2020**, please list details for **all** electricity meters. This will account for electricity used for packhouses processes, as well as electric vehicles used for electric forklifts and work by personnel.

	Activity (e.g. packing line, washing, cooling etc.)	Quantity (kW)
Meter 1		
Meter 2		
Meter of electrical forklifts		
Other(s)		
Notes:		

How much of the total electricity use (%) is estimated for the packaging process (with an assumption that the rest is allotted to transport of products and personnel).

2.7 Water use

For the time period **1 June 2019 to 31 May 2020**.

- What is the total amount of water used to clean bins, packline, equipment etc (***NOT including the waterblaster***) (L)?

2. What sanitiser is used in the cleaning process (e.g. for bins, packline, packhouse floor)?

3. What is the quantity of sanitiser used for the cleaning process (e.g. for bins, packline, packhouse floor)?

4. What is the total amount of water used for water blasting fruit (L)?

5. How much additional water is required every day when avocados are packed (L)?

6. What sanitiser used in the water blaster?

7. What is the quantity of sanitiser used for water blasting the fruit?

2.8 Off-site transport

For the time period **1 June 2019 to 31 May 2020**. Add other items not on the list and other relevant details in the notes section.

Transport activity	Pick-up and/or drop-off location	Type of Vehicle used	Number of trips for given time period
Packaging materials to packhouse			
Fruit from orchard to packhouse			
Packed fruit trays to distributor/retailer			
Fruit sent for oil processing			

Waste fruit to landfill			
Waste fruit to farm as feedstock			
Waste packaging material sent to landfill			
Waste packaging material sent to recycling			
Other			
Notes:			

2.4.9 Fuel use (other)

For the time period **1 June 2019 to 31 May 2020**. Add any other oils or lubricants not included in this list.

Fuel type	Activity (e.g. petrol for on-site transport - forklifts)	Total quantity (litres)
Diesel		
Petrol		
Lubricants		
CNG		
Other		
Notes:		



Life cycle assessment questionnaire for exporters

1 General exporter data

Name of exporter	
Name of person completing this survey	
Period chosen for data collection	1 June 2019 to 31 May 2020
Do you solely export - or pack and export - avocados?	
What are your export markets for avocados?	
Where is your local market for avocado (e.g. nationwide distribution or a specific region – BOP only)?	
Please state the transport routes within New Zealand for avocados that are on the domestic market (e.g. transported from named packhouse to T&G in Auckland via a truck)	
Please state the transport routes within New Zealand for avocados that are exported (e.g. transported from named packhouse to Ports of Tauranga)	

Notes:	

Ports of Tauranga and Ports of Auckland will provide data for port activities (e.g. cranes, trucks used within the shipyard for loading and unloading the container).

2 Transport

Please include all transport activities for the period **1 June 2019 to 31 May 2020**. Please add any other items not listed and/or add relevant details in the notes section.

Transport activity	Destination	Volume	Vehicle/ship/plane details*	Type of fuel used by vehicle/ship/plane	Distance travelled (km)	Average time to reach destination (days)	Fuel consumption for trucking (specify whether per truck or pallet)	Fuel consumption for shipping (specify whether per ship or container)
Packed fruit trays to distributor/retailer for local market sales								

Transport activity	Destination	Volume	Vehicle/ship/plane details*	Type of fuel used by vehicle/ship/plane	Distance travelled (km)	Average time to reach destination (days)	Fuel consumption for trucking (specify whether per truck or pallet)	Fuel consumption for shipping (specify whether per ship or container)
Packed fruit pallets in container to port	Auckland							
	Tauranga							

Transport activity	Destination	Volume	Vehicle/ship/plane details*	Type of fuel used by vehicle/ship/plane	Distance travelled (km)	Average time to reach destination (days)	Fuel consumption for trucking (specify whether per truck or pallet)	Fuel consumption for shipping (specify whether per ship or container)
Shipped container	Busan, South Korea							
	Brisbane, Australia							
Air freighted container **	Busan, South Korea							
	Brisbane, Australia							
Other(s)								

Transport activity	Destination	Volume	Vehicle/ship/plane details*	Type of fuel used by vehicle/ship/plane	Distance travelled (km)	Average time to reach destination (days)	Fuel consumption for trucking (specify whether per truck or pallet)	Fuel consumption for shipping (specify whether per ship or container)
Notes (in particular, please note if any of the data above is abnormal due to Covid restrictions):								

* Type of vehicle used (e.g. diesel powered 40-t lorry, size of ship, Boeing 777 etc.)

** In the case of air freight, please state how full the cargo hold usually is.

Rationale for Assumptions, Data Choices, and Miscellaneous

General Assumption

According to Ecoinvent, data on transport are calculated for an average load factor and include empty return trips. So, backhauling is incorporated to a certain extent in the datasets, and the distance was therefore not doubled, on the assumption that trucks, trains, planes, and container ships did not return empty.

Table D1 Packaging and Distribution stage assumptions and data choice justifications

<u>Sub-Stage</u>	<u>Assumption and/or modelling choice</u>	<u>Dataset Choice</u>	<u>Justification</u>
Avocados at packhouse		Dataset for pallet production used as proxy to model manufacturing of wooden bins	No Ecoinvent dataset was found for wooden boxes, so the pallet production dataset was used to model wooden box manufacturing. Several companies were identified that manufacture pallets as well as wooden bins for horticultural packaging in New Zealand, so this approach was considered appropriate to model wooden bin manufacturing.
	Packhouses source wooden bins from Auckland		Pallet manufacturers identified in the North Island (closest to Tauranga) were mainly in Auckland.
Waterblasting and Sanitising Avocados	Water comes from town supply		No data available on source of water supply. Therefore, town supply was chosen as the default source as this would account for electricity used for water treatment and distribution losses as well.
		Dataset for Caustic Soda Production used as proxy for harvestcide	Packhouses use harvestcide (main ingredient Bromochlorodimethylhydantoin or BCDMH) and caustic soda (sodium hydroxide). Ecoinvent does not have a dataset for

			harvesticide, so the caustic soda dataset was chosen as a proxy.
		Dataset for diesel combustion is used as a proxy for LPG combustion	While there are Ecoinvent datasets for LPG production, there are no datasets to model the impacts attributed to combustion of LPG. As per the MfE (2020) detailed guide to measuring emissions, the emission factor of LPG in stationary combustion is 3.02 Kg CO ₂ eq./kg of LPG burned, and the emission factor for diesel burned in stationary machinery is 2.66 kg CO ₂ eq./L of diesel. 1 l of diesel = 0.86 kg diesel. Therefore, the GWP value/kg diesel = 2.66/0.86 = 3.1Kg CO ₂ eq./kg diesel. This is approximately the same as the emission factor for LPG and therefore the dataset for diesel combustion was used as a proxy for LPG combustion.
		Ecoinvent dataset for diesel combustion used as a proxy for LPG combustion is altered to lower GWP values.	Ecoinvent has two relevant datasets (burning diesel in stationary machines) with outputs in terms of energy (MJ): diesel burned in diesel-electric generating set (10MW); and diesel burned in diesel-electric generating set (18.5MW). They each have an output of 1MJ energy from diesel burned. The GWP values for these two datasets are 0.0862 and 0.254 kg CO ₂ eq./MJ. 1kg of LPG = 49MJ energy (Elgas, 2021). Therefore, the above two GWP values equal 4.2 and 12.3 Kg CO ₂ eq./kg of LPG. The former is closest to the GWP/MJ value obtained earlier but is 28% higher than the emission factor provided by MfE (2020). So, it was decided to use this dataset for LPG combustion diesel inputs for company travel, after reducing its CO ₂ outputs by 28%.
Packline Sub-stage	Water comes from town supply		Same as in above sub-stage above
		Ecoinvent CH (Switzerland) dataset for milled and packed quicklime	Ecoinvent datasets for loose and/or milled and packed quicklime have GWP values ranging from 1.11 to 1.25 kg CO ₂ eq./kg product. According to IPCC 2006, the emission factor for high calcium lime is 0.75kg CO ₂ eq. / kg of lime with 95% purity. There is no emission factor for quicklime (also known as burnt lime), but according to emissions trading bulletin by the Ministry for the Environment of 2009, quicklime production emissions are 0.79 kg CO ₂ eq./kg lime. However, this emission factor only considers the chemical

			processes involved in manufacturing quicklime, and not the 'cradle' operations of mining, extraction, and transport of lime. Thus, it was inferred that the ecoinvent datasets provide fairly accurate information about total emissions. For this study, the CH (Switzerland) dataset for milled and packed quicklime (which has a GWP of 1.12 Kg CO ₂ eq./kg of product) because this would include mining, extraction, packaging, and transport of to the factory and, manufacturing conditions were assumed to be similar to practices in New Zealand, where quicklime is also produced.
	Quicklime comes from Omya NZ LTd., whose plant is at Te Kuiti near Waitomo.		Closest quicklime manufacturer to Tauranga.
		European dataset for soap manufacturing used for sanitiser	Products like Biozyme and Zetapy are used when disinfecting the packlines. No Ecoinvent dataset available for these, therefore the closest proxy (soap production in Europe) was used as a proxy. This does not include transport to consumer, so it is more representative than the market activity dataset.
		European dataset for flat pallet production	No NZ dataset on Ecoinvent. Pallets in NZ are manufactured from sustainably sourced wood, and it was assumed that the European dataset for pallet production would be the best proxy as European manufacturing practices also tend towards sustainability.
	Pallets come from Auckland manufacturer		Pallet manufacturers identified in the North Island (closest to Tauranga) were mainly in Auckland.
		European dataset for corrugated board (cardboard packaging)	There are three Relevant Ecoinvent datasets – one for Canada/Quebec, one for Europe and a third global average. The GWP values of these three datasets are 0.91, 0.5 and 0.97 kg CO ₂ eq./kg of product, respectively. A recent study on the environmental impacts of packaging (Io-Iacono Ferrera et al., 2021) used an emission factor of 1.02 Kg CO ₂ eq./kg of product. The European and global average values are close to this value.

			Assuming that New Zealand packaging manufacturing processes would be aligned with European ones, it was decided to use the European dataset for cardboard packaging.
	Cardboard packaging comes from Auckland		Transport was modelled for distance to Oji Fibres – one of the largest suppliers of cardboard packaging to packhouses. The company has manufacturing plants in Auckland and Hamilton, so it was assumed that the cardboard comes from their plant in Auckland.
	Exclusion of biogenic carbon		Carbon stored in cardboard and wooden pallets were not included in the study as it was assumed that this sequestered carbon would be released back to the atmosphere on a short timescale. As per European Commission et al. (2010), ' <i>carbon storage should only be quantitatively considered if this is explicitly required to meet the goal/s of the study. Otherwise, i.e., per default, temporary carbon storage and the equivalent delayed emissions and delayed reuse/recycling/recovery within the first 100 years from the time of the study shall not be considered quantitatively</i> '. Thus, other studies Abejón et al. (2020) included biogenic carbon in their study because the goal of the study was to understand why plastic packaging is environmentally preferable to cardboard. Similarly, Lo-Iacono-Ferreira et al. (2020) conducted a detailed study of the carbon footprint of transporting Spanish fruits and vegetables in cardboard boxes, and as per the ISO 14067 standard, were required to account for biogenic carbon separately. Moreover, it has been noted that for CFs of fast-moving products like packaging materials, accounting for biogenic carbon may inaccurately inflate carbon credits (Sazdovski et al., 2024). Thus, excluding biogenic carbon storage was considered appropriate for this study, given its overall aim was not to conduct a full-scale CF, but assess the environmental impact profile of the post-harvest stages of the supply chain for the purpose of developing VSS criteria.
	Plastic stickers and strappings		These are commonly used articles, with several suppliers in Tauranga, so it was assumed that they were made in Tauranga.

	are made in Tauranga		
		Production of all plastic packaging components (stickers, strapping and EAN label backing) was modelled with two datasets: 1) GLO: market for polyethylene terephthalate, granulate, amorphous, recycled; and 2) RoW: extrusion of plastic sheets and thermoforming, inline	These plastic components are made of polypropylene or polyethylene terephthalate granules or pellets by extruding them into sheets. Therefore, two different processes involved – one for the manufacture of the granules and one service activity for the inline extrusion and thermoforming of plastic sheets for the food industry. This service activity does not include the production process for the granules.
	Paper for the EAN labels is sourced from New Zealand Pulp and Paper (NZPP)	Dataset used: RER: paper production, woodfree, uncoated, at integrated mill	NZPP is the main paper manufacturer in NZ. Also, they have integrated manufacturing processes, i.e., they make pulp and paper at the same location
	Leased plastic crates and wooden pallets not modelled		Leased crates and pallet are re-used several times and are in circulation a long time. Therefore, they were considered capital equipment and were excluded from the model.
	Wooden bins used for transporting packed avocados to the domestic market were not modelled		A small number of wooden bins are used for transporting fruit to the domestic market, but the fruit weight per bin unknown. Given that the quantity of fruit transported in wooden bins was very small, this was excluded from the model.
	Standard cardboard box		No standard cardboard box dimensions attributed to avocados are available as they vary between packhouses (Packhouse

	dimensions unavailable		representatives, Pers. Comm., March 2018) and the level of detail in the data differed between respondents. For example, Packhouse 1 classified their packaging into 'single layered trays with pocket packs for export and bulk, loose-filled boxes for domestic markets', whereas Packhouse 2 provided data for 19 different pack types across five main categories – bulk loose fill, bulk with pocket packs, wooden bins, crates, and single layered trays for the domestic and export markets.
Cooling and Storage		European dataset for chlorodifluoromethane	Although USA is the most significant manufacturer of refrigerants (with China gaining ground in recent times as well), the only Ecoinvent datasets available for R22 were from Netherlands, Europe, and the global average. The most representative one was Europe.
	Transport modelled from Germany, but road and rail freight transport in Germany not modelled separately		The European dataset chosen is a market activity dataset and includes transportation to customers within the European region. This includes 13km/kg by freight train and 51 km/kg by road. So, the road and rail freight distance was not modelled separately – only the distance by sea to New Zealand and on-road distance within New Zealand to the packhouses was modelled separately.
	80% of total electricity in packhouses is used by the coolstore		Electricity use by coolstores dominate the total electricity use of the packhouse. Mithraratne et al. (2010) noted coolstore contribution to total electricity use to be between 72-82%. Based on this, and consultation with an industry expert (Andrew Barber, Pers. Comm., 27 April 2022), it was decided to allocate 80% of total electricity use in the packhouse to cooling and storage operations.
	Share of electricity used for avocados in the coolstore is based on		See Section E for calculation and rationale

	weight of avocados and time of storage, whereas share of electricity used for avocados on packline, and refrigerant top up in the coolstore is calculated based on weight of avocados alone		
	Avocados sent to oil are also stored in the coolstore till they are transported out		This assumption is based on the view that the avocados for oil may not be transported out immediately after they are graded and might need to be stored for a few days.
	No refrigerant values for PH2		Packhouse 2 did not need a refrigerant top up in the period of data collection, and so Freon emissions were registered only for Packhouse 1.
Post-Packaging waste and company transport	Petrol used for company transport in packhouse 2 excluded from model		Very small value – 115 L. This referred to total petrol use by the packhouse for company transport and is associated with all fruit. Therefore, it was excluded because it was deemed to have an insignificant contribution per kg of avocado.

	Company transport was excluded from the baseline model, but included in an additional scenario analysis		Data were requested for 'on-site' fuel use to account for fuel / electricity used by forklifts and other on-site transport associated with avocado packaging (company transport), and fuel/electricity used by vehicles for business purposes (business transport, e.g. grower services, Avogreen agrichemical programme, other personnel travel etc.). However, the packhouses did not provide this disaggregated data. PH 1 provided a value for total on-site diesel use (not distinguishing between business and company transport), whereas PH 2 stated that all their diesel use was for business purposes only as they only used electric forklifts. Therefore, for both packhouses, 'on-site' diesel use was attributed entirely to business transport and was not included in the baseline. This was modelled in the additional scenario analysis by using the average of the two 'on-site' diesel use values⁵⁷. The International EPD System specifically excludes "business travel of personnel" from the product carbon footprint (EPD International, 2019, Section 4.3.1.2). Also, no reference to it in the ISO standards or in the European guidelines. It was included as a sensitivity analysis to determine whether there is in fact any contribution of this process to overall impacts and if so, how much.
		Passenger car dataset altered to model company transport impacts	The GWP for this Ecoinvent dataset is 0.3 kg CO₂ eq./km travelled. As per MfE (2020), the average GWP for diesel cars manufactured after 2015 is 0.2 Kg CO₂ eq./km travelled. Since this is almost 33% lesser than the GWP for the Ecoinvent, an alternate dataset was created by reducing the CO₂ emissions 33%.
Extending system boundary	Post-port activities		After the fruit arrive in Australia, they are transported to a facility where they undergo quarantine and fumigation (if required),

⁵⁷ Since the proportion of diesel use by forklifts (if any) in the total on-site diesel use is not significant, any associated potential environmental impacts are also likely not significant.

	including ripening chamber and transport to RDC and retailer		followed by quality checks. At this stage, fruits with rot are discarded and a fruit loss of ~5% occurs at this stage. The good fruit are then placed in ripening chambers (customers in countries like Australia demand ripe fruit ready for sale) and 'triggered' to ripen at a particular temperature to meet the RDC specifications. The ripening chambers are temperature controlled (16 degrees C) and exposed to ethylene to trigger the ripening process, which can take up to 2-5 days. Ripened fruit are then transported by reefer lorries to the RDC and further distributed on to supermarkets.
Miscellaneous	The miscellaneous diesel use by contractor was excluded from the model		Very small value – 298 L for 287 km travelled. This referred to total miscellaneous diesel use by contractors for all packhouse activities for all fruit and therefore it was excluded because it was deemed to have an insignificant contribution per kg of avocado.
		For almost all local transport in the 'post-harvest transport and packaging stage', the dataset RER: Transport, freight, lorry, 7.5-16 metric ton, EURO 6 was used ⁵⁸	The MfE (2020) detailed emissions guide provides emission factors for light commercial vehicles manufactured between 2010-2015, as well as post-2015. The average for both periods for diesel commercial vehicles is 0.23 kg CO ₂ eq./km travelled. Euro 6 is the latest in the EURO categorization and this dataset has a GWP value of 0.21 kg CO ₂ eq./t.km (same as the Euro 5 dataset). Since this is in line with the values noted by MfE (2020), it was decided to use this dataset.
	Diesel potentially used for forklifts is included under		PH 2 provided data for 'on-site' fuel use, clearly stating that no fuel was used for their forklifts, 75% of which are electricity powered. However, this still leaves 25% of their forklifts which must use other fuel like diesel, but these are not accounted for. Their 'on-site' diesel use is only for 'business' purposes like the Avogreen programme or grower services. PH 1 only mentioned their 'on-site'

⁵⁸ The 16-32 metric tonne dataset (EURO 6) was used in some isolated cases, e.g. transporting manufactured pallets to the packhouse, since there was no data about the exact mode of transport and an assumption was made in this case.

	'company transport for business purposes'		diesel use but did not mention how much of that is used for business purposes and for forklifts. They also did not mention what % of their forklifts are electricity-operated. As such, disaggregation of on-site fuel use for forklifts was not available and therefore, it was included in 'fuel use for company transport for business'. However, since PH 2 had more specific data, it was expected that using the average of the two would provide a better picture of the actual fuel used for business purposes by the packhouses.
Distribution Stage	No fruit or packaging is lost on any of the voyages.		Although this is not representative of the real-world, for the purposes of this study, zero fruit losses were assumed during the post-packaging transport stage, because the system boundary was the port/drop-off point. In case of an expanded system boundary, fruit losses would need to be modelled.
	For road transport, backhauling was assumed i.e. trucks, trains, planes and container ships did not return empty (50% backhauling was assumed).	-	This assumption was made because it was not possible to obtain exact logistical data from the exporter due to the inherent variability in data. "While trucks return empty 50% of the time, the rest of the trips do have some amount of backhauling, as we try to load as much as we can on return trips. It all depends on what kind and how much cargo needs to be transported on the way back – and this is highly variable" (Brett Marsh Transport, Pers. Comm., June 2021). The Ecoinvent datasets used to model transport-related impacts consider an average load factor and include empty return trips (see general assumption on transport).
	For road transport, trucks were assumed to return straight to the haulage company without making any	-	In reality, the return trip route for trucks may vary, depending on whether they return to the packhouse or some other location for another pick-up or whether they travel straight back to the haulage company. In the absence of specific route distance data, a conservative approach was adopted for modelling the return trip in keeping with the suggestions from the haulage company and the return trip was modelled for a straight route back without detours. "While the return route may vary a bit, generally a trip straight back to the haulage company would be approximately the same

	detours.		distance as the other way round." (Brett Marsh Transport, Pers. Comm., June 2021).
		Dataset chosen for local road transport to ports, airports, metroport and first point-of-sale is "GLO: market for transport, freight, lorry with reefer, cooling"	There are two Ecoinvent datasets on refrigerated truck transport (for large 16-32 metric tonne and >32 metric tonne lorries) for vehicle classes EURO 3,4,5, & 6, using a combination of two refrigerants (CO ₂ and R134a). Of the two, only this dataset showed environmental impact scores consistent with trucks of this size, whereas the impact scores of the other dataset were much higher in line with use of small lorries (3.5-7.5 metric tonnes). Therefore, it was decided to use the former.

Input and LCI Data

LCI Data for transport and electricity datasets⁵⁹

- a) RER: transport, freight, lorry, 7.5-16 metric ton, EURO6 (diesel; 32% utilisation rate based on average load factor of 3.29 t and GVW (Gross Vehicle Weight) of 9.29 t)
- b) RER: transport, freight, lorry, 16-32 metric ton, EURO6 (diesel; 37% utilisation rate based on average load factor of 5.79 t and GVW of 15.79 t)
- c) GLO: transport, freight, sea, container ship (heavy fuel oil; 70% utilisation rate)
- d) RER: transport, passenger car, medium size, diesel, EURO5 (petrol)

⁵⁹ Ecoinvent data on transport are calculated for an average load factor and include empty return trips.

- e) GLO: Market for transport, freight, lorry with reefer, cooling (diesel; 45% utilisation rate assumed, based on average of average load factors of 16-32 t and >32 t trucks used in this transport mix)
- f) GLO: Market for transport, freight, train with reefer, cooling (diesel; 50% utilisation rates assumed)
- g) GLO: Market for transport, freight, sea, container ship with reefer, cooling (heavy fuel oil, 70% utilisation rate)
- h) GLO: Market for transport, freight, aircraft with reefer, cooling (kerosene; 50% utilisation rate assumed)
- i) GLO: Market for transport, freight, sea, ferry (heavy fuel oil; 50% utilisation rate)
- j) NZ: Electricity 2018-2020 average LV supply (incl. T & D & Solar)

Table D2 Avocado quantities processed in PH1 and PH2

	PH1	PH2
Total avocado brought in (kgs)	6,112,093	5,548,788
Avocados packed for export (kgs)	3,403,598	2,823,305
Avocados packed for domestic market (kgs)(excluding oil and waste)	1,802,568	2,260,691
Total avocados packed for transport (kgs)	5,206,166	5,083,996
Avocados sent to oil (kgs)	886,508	421,709
Waste avocados (rejects, undersized, class 3 etc., used for stockfeed and local market, unpackaged) (kgs)	19,419	43,083
Total kiwifruit handled in packhouse (kgs)	24,500,000	63,102,926
Total fruit handled in packhouse (kiwifruit + avocados) (kgs)	30,612,093	68,651,714
Percentage of total avocados handled to total fruit handled	20%	8%

Table D3 Total avocados packed for exports (kg) and PH weights for weighted average

Total packaged for export PH1	3403598	Weight PH1	0.55
Total Packaged for export PH2	2823305	Weight PH2	0.45
Total packaged for export PH1+PH2	6226903		

Table D4 Generic Data – Secondary Sources / Assumptions for background data

	<u>Values</u>	<u>Comments</u>
Wooden Bins	191 km from Auckland to packhouses	Pallet manufacturers identified in the North Island (closest to Tauranga) were mainly in Auckland. Distance from Auckland to Packhouse 1 is 161 km and to Packhouse 2 is 221 km. For this study, the average of these two (191 km) was used.
Wooden Pallets	Same as above	Same as above
Caustic Soda	-	The Ecoinvent dataset for caustic soda includes transport to consumer, so no additional transport was modelled
Quicklime	145 kms from Omya NZ Ltd. plant to retailer in Tauranga and approximately 30 kms from retailer to packhouses in Tauranga.	-
Soap (disinfectant)	336 km to Picton, 100 km by ferry, 523 kms to Tauranga retailer from wellington and 30 km from retailer to packhouse.	Biozyme multi is manufactured in Christchurch
Cardboard packaging	202 kms by road	Distance from Oji Fibres plant in Auckland to PH 1 and 2 is 172 km and 232 km by road, respectively. For this study, the mean of these two was used.
Plastic stickers and strappings	27 km by road	Distance travelled to transport them from manufacturer/retailer in Tauranga was the mean of 23 kms to Packhouse 1 and 30 km to Packhouse 2.
EAN labels	295 km by road; 27 km by road	EAN labels are made of paper and have a plastic backing. Paper is assumed to be sourced from NZPP, located in Whakatu, Hawke's Bay (from Tauranga) over 295 km. No transport is modelled for the plastic because it is assumed to come from Tauranga over a short distance. EAN labels are assumed to be manufactured in Tauranga and then transported to the packhouse over 27 km – the mean of 23 kms to Packhouse 1 and 30 km to Packhouse 2.
Refrigerant	27,700 km by ship; 207 km by road; 27 km by road	Chlorodifluoromethane or R22 or HCFC22 was modelled using a European market activity dataset, which includes transportation to customers within the EU region. This includes 13km/kg by freight train and 51 km/kg by road. Therefore, the only transport modelled included the shipping distance of 27,700 kms to Auckland, Auckland to Tauranga regional storage by road (207 km), and from Tauranga city retailer to

		packhouses (27 km).
Water	Electricity use associated with treatment of town water supply = 0.0023 MJ/kg of water Water distribution losses = 18%	Justification in production (orchard) stage section
Waste packaging	15 km to recycling centre	-
Miscellaneous	Pallet unit conversion – 1 unit = 20.7 kg	-
	LPG unit conversion - 1 kg = 49 MJ	-

Table D5 Data from Packerhouses (total, for all fruit processed) – disinfectants, refrigerants, electricity, water, waste packaging, fuel

<u>Sub-Stage</u>	<u>Packhouse 1 Values</u>	<u>Packhouse 2 Values</u>	<u>Data Source and Comments</u>
Distance from orchard to packhouse	15 km	20 km	Assumed
Wooden Bins	175 bins, 55 kg each*	30 bins, 60 kg each	Measured
Caustic Soda	110 L	287 L	Measured
Soap (disinfectant)	20 L	79 L	Measured. 55.8 L Citrox and 23 L Zetapy
Refrigerant	24 kg*	-	Measured. PH 2 did not require any refrigerant top up in the study period
Electricity	7,978,258 kWh	13,500,726 kWh	Measured
Waste packaging (cardboard)	30,000 kg	60,644kg	Measured

Waste packaging (plastic)	-	1,906 kg of shrinkwrap	Measured
Fuel (Diesel) contractor transport and packhouse activities	9,185 L **	11,238 L**; 287 L miscellaneous	Measured. The miscellaneous diesel use by contractor was excluded from the model due to very small amount attributed to 1 kg of avocados
Fuel (Diesel) business transport	165,000 L	13,062 L*	Measured
Fuel (Petrol) contractor transport and packhouse activities	-	-	
Fuel (Petrol) business transport	-	115 L*	The petrol use for company transport was excluded from the model due to very small amount attributed to 1 kg of avocados
Fuel (LPG)	-	900 kg*	Measured
Water (waterblasting and sanitizing fruit)	250,000 L	500,000 L	Measured
Water (cleaning bins and packline)	1,425,000 L	151,700L	Measured

* Attributed to avocados only; ** For transporting avocados from orchard to packhouse, one way

Table D6 LCI data (per kg of avocados packed) for post-harvest transport and packaging stage

<u>Sub-stage</u>	<u>Input</u>	<u>Packhouse 1 Values</u>		<u>Packhouse 2 Values</u>		<u>Data Source and Comments</u>
		Export	Domestic – bulk loose fill cardboard boxes, no pocket packs	Export	Domestic – plastic crates	
Transport – orchard to packhouse	Wooden Pallet (kg)	0.0016		0.00032		
	Lorry 7.5-16 metric ton (t.km)	0.017		0.023		
Waterblasting,	Water (L)	0.01		0.009		

sanitising and drying	Caustic Soda solution (L)	3.6E-06		4.2E-06		
	LPG (kg)	-		1.6E-04		
Packline (Sorting, grading, packing and washing)	Water (L)	0.055		0.0026		
	Quicklime (kg)	0.004		0.0042	0	
	Sanitiser (L)	6.5E-07		1.2E-06	0	
	Wooden pallets (kg)	0.0201	0.0210	0.096	0.0139	Measured
	Cardboard (pocket packs, corrucup, boxes, single layer tray, bulk tray, corner boards, pallet crowns) (kg)	0.1201	0.06	0.105	0	Measured
	Plastic (Stickers, strapping) (kg)	0.0002		0.0006		
	EAN label (kg)	-		0.0002	0	Measured. PH 1 did not provide data on EAN labels
	Electricity (kWh)	0.052		0.04		
Cooling and storage	Electricity (kWh)	0.14		0.12		
	Refrigerant (kg)	4E-06		0		
Post-packaging (waste to recycling)	Cardboard	0.006		0.012		
	Plastic granules	0		0.0004		
	Transport to recycling centre - lorry 7.5-16 metric ton (t.km)	0.0001		0.0002		
Sensitivity Analysis	Business transport (for sensitivity analysis) (m)	65	-	27.3	-	

Table D7 Weight of packaging for export and domestic scenarios (kg/kg avocados)

Scenario	PH1	PH2	Average
SLT for export	0.144	0.206	0.175
BLF domestic	0.0812	-	-
PC domestic	-	0.0145	-

Table D8 Packaging quantities and their equivalents for distribution stage

Quantity of avocados (kgs) /Tray Equivalent (TE)	5.5
TEs/pallet (when transporting only locally)	160
Pallets/truckload	26
Pallets/PMC ⁶⁰	5
TEs/PMC	560
TEs/air pallet (when transporting to Mainfreight for export by air)	112
TEs/Forty Foot Equivalent (FEU) ⁶¹	3,360

Export – Transport by Sea

Loading Ports: Auckland (AUCK) and Tauranga (TRG)

Destinations: Brisbane (BNE), Melbourne (MEL), Sydney (SYD), Busan (BSN)

Transport via: Road, Rail and Ship

⁶⁰ PMC is a specific type of large pallet used to transport avocados via airplane. These avocados are packed in trays, which are in turn stacked in air pallets that then go into a PMC. On average, there are six PMCs/flight.

⁶¹ An FEU or Forty-foot Equivalent Unit is a unit of transport used when shipping freight via sea. It can refer to either one 40-foot container or two 20-foot containers. On average, for avocado shipments being shipped by sea assumes a loading of 3360 TEs, which constitutes approximately 95% of a full container load.

Table D9 Tray Equivalents (TEs) from loading ports to destination ports

	<u>Loading port</u>			<u>Destination Port</u>			
Packhouse	AUCK	TRG	TE's	BNE	MEL	SYD	BSN
TREV	54,790	378,660	433,450	225,926	25,020	176,220	6,284
APATA	39,008	512,175	551,183	304,638	30,248	195,013	21,284
DMS	34,134	228,540	262,674	106,820	3,165	144,790	7,899
KP	54,989	277,734	332,723	171,862	704	153,693	6,464
GM	73,401	179,269	252,670	187,231	-	65,439	-
FN	67,982	116,741	184,723	122,513	-	62,210	-
TOTAL	324,304	1,693,119	2,017,423	1,118,990	59,137	797,365	41,931

Table D10 FEUs from loading ports to destination ports

	<u>Loading Port</u>			<u>Destination Port</u>			
Packhouse	AUCK	TRG	FEU	BNE	MEL	SYD	ICN
TREV	16	113	129	67	7	52	2
APATA	12	152	164	91	9	58	6
DMS	10	68	78	32	1	43	2
KP	16	83	99	51	0.2	46	2
GM	22	53*	75	56	-	19	-
FN	20	35*	55	36	-	19	-
TOTAL	97	504	600	333	18	237	12

*via metroport rail

Table D11 TEs shipped per port

	<u>Auckland</u>	<u>Tauranga</u>

Brisbane	222,141	896,849
Melbourne	9,365	49,772
Sydney	92,798	704,567
Busan	0	41,931
Total	324,304	1,693,119

Table D12 TEs (%) shipped by destination

	<u>Auckland</u>	<u>Tauranga</u>
Brisbane	68%	53%
Melbourne	3%	3%
Sydney	29%	42%
Busan	0%	2%
Total	100%	100%

Table D13 Road and rail distances to New Zealand ports

<u>Packhouse</u>	<u>BM to Packhouse</u>	<u>BM to Tauranga Port</u>	<u>BM to Auckland Port</u>	<u>Total BM to Auckland Port</u>	<u>SCALES to Packhouse</u>	<u>Packhouse to Auckland Port</u>
TREV	36	27	238	274		
APATA	23	29	180	203		
DMS	12	17	192	204		
KP	46	51	165	211		
GM					174	166
FN					346	332

* Distance from Auckland port to Metroport by road = 22 km

* Distance between Auckland and Tauranga ports via Metroport = 228 km

Table D14 Distances from New Zealand ports to overseas ports

<u>PORT</u>	<u>Brisbane</u>	<u>Melbourne</u>	<u>Sydney</u>	<u>Busan (South Korea)</u>
Auckland	2,839	2,995	2,463	11,595
Tauranga	3,020	3,805	2,643	11,775

Export – Transport by Air

Table D15 Tray Equivalents (TEs) from Mainfreight loading port in Auckland to destination airports in Australia and South Korea

<u>Packhouse</u>	<u>Loading Port</u>	<u>TEs</u>	<u>BNE</u>	<u>MEL</u>	<u>SYD</u>	<u>ICN</u>
TREV	Auckland	19,775	5,259	3,176	1,396	9,944
APATA	Auckland	10,016			176	9,840
DMS	Auckland	12,005	5,239		6,654	112
KP	Auckland	8,856	2,100		6,756	
GM	Auckland	3,739	696		3,043	
FN	Auckland	7,912	3,344		4,568	
TOTAL		62,303	16,638	3,176	22,593	19,896

Table D16 Road distances between haulage company, packhouses and Mainfreight

<u>Packhouse</u>	<u>Haulage company 1 to Packhouse</u>	<u>Haulage company 2 to Packhouse</u>	<u>Packhouse to Mainfreight</u>	<u>Total km</u>
TREV	36		227	263
APATA	23		169	192
DMS	12		180	192

KP	46		153	199
GM		15	185	200
FN		170	351	521

Table D17 Distances (km) from Mainfreight in Auckland to overseas airports in Australia and South Korea

<u>Brisbane</u>	<u>Melbourne</u>	<u>Sydney</u>	<u>Incheon (South Korea)</u>
2,292	2,636	2,158	9,620

Domestic Transport – North Island

Table D18 Locations of avocado drop-off points in North and South Islands

North Island	% Volume (TEs) transported to each location of total volume transported domestically	South Island	% Volume (TEs) transported to each location of total volume transported domestically
Auckland	74	Christchurch	2.2
Hamilton	0.8	Dunedin	0.3
Hastings	0.4	Nelson	0.7
Kerikeri	2.9		
New Plymouth	0.3		
Palmerston North	0.4		
Tauranga	0.6		
Te Puna	14.7		
Wellington	2.5		

Table D19 Volumes (TEs) and distances from packhouses to the drop-off point in Auckland

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	266643	170	35
DMS	78460	190	29
Far North Packers	53256	340	170
Golden Mile Packers	152127	174	15
Kauri Pak	113465	164	46
Trevelyan	22465	227	36

Table D20 Volumes (TEs) and distances from packhouses to the drop-off point in Hamilton

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	1505	120	36
DMS	1846	107	29
Far North Packers			
Golden Mile Packers	1094.9	282	15
Kauri Pak	3262	117	46
Trevelyan			

Table D21 Volumes (TEs) and distances from packhouses to the drop-off point in Hastings

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	1087	315	36
DMS	761	303	29
Far North Packers			
Golden Mile Packers	563.94	588	15
Kauri Pak	1196	337	46
Trevelyans			

Table D22 Volumes (TEs) and distances from packhouses to the drop-off point in Kerikeri

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	24350	420	36
DMS			
Far North Packers			
Golden Mile Packers	2221.11	90	15
Kauri Pak	133	404	46
Trevelyans			

Table D23 Volumes (TEs) and distances from packhouses to the drop-off point in New Plymouth

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	371	321	36
DMS	601	309	29

Far North Packers			
Golden Mile Packers	333	519	15
Kauri Pak	1842	341	46
Trevelians			

Table D24 Volumes (TEs) and distances from packhouses to the drop-off point in Palmerston North

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	1091	407	36
DMS	797	395	29
Far North Packers			
Golden Mile Packers	226.6	674	15
Kauri Pak	1753	429	46
Trevelians			

Table D25 Volumes (TEs) and distances from packhouses to the drop-off point in Tauranga

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	686	25	36
DMS	2125	13	29
Far North Packers			
Golden Mile Packers	403.46	366	15
Kauri Pak	2682	47	46
Trevelians			

Table D26 Volumes (TEs) and distances from packhouses to the drop-off point in Te Puna

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	128427	14	36
DMS	185	1	29
Far North Packers			
Golden Mile Packers			
Kauri Pak	7713	36	46
Trevelyans			

Table D27 Volumes (TEs) and distances from packhouses to the drop-off point in Wellington

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	7283	537	36
DMS	4499	525	29
Far North Packers	5	614	170
Golden Mile Packers	2707	804	15
Kauri Pak	8425	559	46
Trevelyans			

Domestic Transport – South Island

Table D28 Volumes (TEs) and distances from packhouses to the drop-off point in Christchurch

Packhouse	Volume transported (TEs)	Distance travelled/load from packhouse to destination (kms)	Distance travelled from haulage company to packhouse (kms)
Apata	2978	964	36
DMS	4967	953	29
Far North Packers	630	1400	170
Golden Mile Packers	6570	1232	15
Kauri Pak	5244	987	46
Trevelyans			

Table D29 Volumes (TEs) and distances from packhouses to the drop-off point in Dunedin

<u>Packhouse</u>	<u>Volume transported (TEs)</u>	<u>Distance travelled/load from packhouse to destination (kms)</u>	<u>Distance travelled from haulage company to packhouse (kms)</u>
Apata	671	1320	36
DMS	751	1308	29
Far North Packers			
Golden Mile Packers	266.4	1587	15
Kauri Pak	1209	1341	46
Trevelyans			

Table D30 Volumes (TEs) and distances from packhouses to the drop-off point in Nelson

<u>Packhouse</u>	<u>Volume transported</u>	<u>Distance travelled/load from</u>	<u>Distance travelled from</u>

	<u>(TEs)</u>	<u>packhouse to destination</u> <u>(kms)</u>	<u>haulage company to packhouse</u> <u>(kms)</u>
Apata	1188	740	36
DMS	1241	729	29
Far North Packers			
Golden Mile Packers	476.19	1008	15
Kauri Pak	3718	763	46
Trevelyan			

Table D31 Additional export markets – distances to export destinations (km) and LCI values (t.km)

	Shipping from Tauranga (km)	Airfreighting from Auckland (km)	Shipping from Tauranga (t.km)	Airfreighting from Auckland (t.km)
Japan	10768.5	8831	12.66	10.38
China	11410.2	9362	13.41	11.01
Singapore	10683	8403	12.56	9.88
Hong Kong	11340	9164	13.33	10.77
Taiwan	10778.4	8884	12.67	10.44
Thailand	11858.4	9549	13.94	11.23
Vietnam	11463.3	9271	13.47	10.9
Indonesia	9709.2	7657	11.41	9
Malaysia	11079	8698	13.02	10.23
USA (East Coast)	15660	0	18.41	0

USA (West Coast)	10130.4	0	11.91	0
Canada	11401.2	11360	13.4	13.35

Table D32 Post-port stages input and LCI data

New weight for packaged avos considering 5% fruit loss (kg)	1.31	Port to storage facility (km)	24
Road freight to storage facility (t.km)	0.031	Storage facility to RDC (km)	28
Road freight from storage facility to RDC (t.km)	0.037	Total road freight port to RDC	52
Ripening chamber electricity use (kWh/kg avocados)	0.11	RDC to retailer (km)	850
Ripening chamber electricity use (kWh/1.05 kg avocados)	0.12	Total road freight port to supermarket	902
Ripening chamber ethylene bromide use (L)	2 bottles per season. Very minimal, therefore excluded.	Road freight from port to storage facility to RDC (t.km)	0.07
		Road freight from port to supermarket (t.km)	1.2

Calculations

Table D33 PH Values calculated per kg of avocados

Sub-Stage	Processes	Packhouse 1	Packhouse 2
Avocados at packhouse	Avocado transport from orchard to packhouse	Transport: 15 km one way. Bin weight 55kg; Fruit weight per bin 410 kg. Weight of bin associated with 1kg avocados = $55/410 = 0.134$ kg. T.km value = $(1 \text{ kg avocados} + \text{bin weight}) * \text{distance}/1000 = 1.134 * 15/1000 = \underline{0.017 \text{ t.km}}$	Transport: 15 km one way. Bin weight 60kg; Fruit weight per bin 410 kg. Weight of bin associated with 1kg avocados = $60/410 = 0.146$ kg. T.km value = $(1 \text{ kg avocados} + \text{bin weight}) * \text{distance}/1000 = 1.146 * 20/1000 = \underline{0.023 \text{ t.km}}$
		175 bins replaced/year. Bin weight 55kg. Total weight of bins replaced every year for avocados is $175 * 55 = 9625$ kg. Associated weight of replacement bins for 1 kg avocados = $9625 / 6,112,093 = \underline{0.0016 \text{ kgs}}$	30 bins replaced/year. Bin weight 60kg. Total weight of bins replaced every year for avocados is $30 * 60 = 1800$ kg. Associated weight of replacement bins for 1 kg avocados = $1800 / 5,548,788 = \underline{0.00032 \text{ kg}}$
Waterblasting and sanitising fruit	Water	250,000 L for all fruit processed. Volume associated with avocados is $0.2 * 250,000 = 50,000$ L. Water distribution loss of $0.18 * 50,000 = 9000$ L. Total water required = 59,000 L for all avocados. Apportioning to 1kg avocados, $59,000/6,112,093 = \underline{0.01 \text{ L/kg of avocados for waterblasting}}$	500,000 L and applies to all fruit. Volume associated with avocados is $0.08 * 500,000 = 40,000$ L. Water distribution loss of $0.18 * 40,000 = 7200$ L. Total water required = 47,200 L for all avocados. Apportioning to 1kg avocados, $47,200 / 5,548,788 = \underline{0.0085 \text{ L/kg of avocados for waterblasting.}}$
	Sanitiser	110 L caustic soda for all fruit. Apportioning to avocados, $110 * 0.2 = 22$ L. Apportioning to 1 kg avocados, $22 / 6,112,093 = \underline{0.0000036 \text{ L}}$	287 L caustic soda for all fruit. Quantity associated with avocados is $287 * 0.08 = 23 \text{ L}$. Apportioning this to 1kg of avocados, we get $23 / 5,548,788 = \underline{0.0000042 \text{ L/kg of avocados.}}$
	LPG	-	900 kg used for avocados. Apportioning to 1kg of avocados, $900/5,548,788 = 0.00016 \text{ kg LPG/kg of avocados.}$
Sorting, grading, packing, and washing the bins and	Water	1,675,000L for all activities. Water use for previous sub-stage is 250,000 L. Therefore,	151,700L of water for this sub-stage for all fruit Apportioning the water use to avocados

packline		water use for this sub-stage = $1,675,000 - 250,000 = 1,425,000$ L. Water use for avocados = $0.2 * 1425000 = 285,000$ L. Water distribution loss of $0.18 * 285,000 = 51,300$ L. Total water use is $285,000 + 51,300 = 336,300$ L. Apportioning this to 1kg avocados = $336,300 / 6,112,093 = 0.055$ L/kg of avocados.	(8% of total fruit), we get $0.08 * 151,700 = 12,136$ L. Incorporating an 18% distribution loss, $0.18 * 12,136 = 2185$ L. Total water use for avocados in this stage is $12,136 + 2185 = 14,321$ L. Apportioning this to 1kg avocados = $14,321 / 5,548,788 = 0.0026$ L/kg of avocados.
	Quicklime	15,000 kg for all avocados. This lime is be apportioned to the avocados that are packed only for export. This quantity is 3,403,598 kgs. Apportioning quicklime used for 1kg of avocados, we get $15,000/3,403,598 = 0.004$ kg/kg of avocados packed for export.	11,748 kg for all avocados. This lime is to be apportioned to the avocados that are packed only for export. This quantity is 2,823,305kgs. Apportioning quicklime used for 1kg of avocados, we get $11,748/2,823,305 = 0.0042$ kg/kg of avocados packed for export.
	Pallet	See table 2 – Values already provided per kg of avocados	See table 2 – Values already provided per kg of avocados
	Cardboard		
	Plastic (Stickers and Strappings)		
	EAN Labels	-	Value/kg of avocados provided in Table 2. However, calculation of individual plastic and paper components are included here. EAN labels are made of 61% paper (the actual label) and 39% plastic backing. So a process was created for an input of 0.61 kg paper, 0.39 kg LDPE granules, and 0.39 kg extrusion service for an output of 1kg labels. Paper is produced by NZPP located in Whakatu, Hawke's Bay. This is 295 km by road from Tauranga. So, transport was modelled for 0.61 kg paper travelling 295 km to Tauranga = $0.61 * 295/1000 = 0.180$ t.km. No transport is modelled for the plastic because it was assumed that it is sourced from nearby in Tauranga itself. At Tauranga, the EAN labels are manufactured and then transported 27 km

			(0.027 t.km for 1kg labels) from Tauranga to the packhouses
	Sanitiser	20 L. Apportioned to 1 kg of avocados, $0.2 * 20 = 4\text{L}$; $4/6112093 = \underline{0.00000065\text{L/kg of avocados.}}$	55.8 L Citrox and 23 L Zetapy. Total sanitiser use = 78.8 L. Apportioning to 1kg avocados, $0.08 * 79 \text{ L} = 6.3 \text{ L}$; $6.3/5,548,788 = \underline{0.0000012 \text{ L/kg of avocados.}}$
	Electricity	Total electricity use in packhouse for all fruits is 7,978,258 kWh. Of the total, 80% is assumed to be used by coolstore. Therefore, electricity used for all fruits in this sub-stage. is $0.2 * 7,978,258 = 1,595,651 \text{ kWh}$. Based on the product split allocation in Table 6, the electricity use for avocados on the packline is 20% of the above value = $0.2 * 1,595,651 = 319,130 \text{ kWh}$. Apportioning to 1 kg avocados, $319,130/6,112,093 = \underline{0.052 \text{ kWh/kg of avocados going through the packhouse.}}$	Total electricity use in packhouse for all fruits is 13,500,726 kWh. Of the total, 80% is assumed to be used by coolstore. Therefore, electricity used for all fruits in this sub-stage is $0.2 * 13,500,726 = 2,700,145 \text{ kWh}$. Based on the product split allocation in Table 6, the electricity use for avocados on the packline is 8% of the above value = $0.08 * 2,700,145 = 216,012 \text{ kWh}$. This applies to all avocados. Paring down to 1kg avocados, $216,012 / 5,548,788 = \underline{0.04 \text{ kWh/kg of avocados.}}$
Cooling and Storage	Refrigerant top up	24 kg refrigerant (R22) top up associated with avocado storage. The product split calculation in Table 6 does not apply because the entire quantity is for avocados already mentioned. Apportioning to 1kg avocados, we get $24/6,092,674 = \underline{0.000004\text{kg/kg avocados stored in coolstore.}}$	-
	Electricity	Total avocados stored in the coolstore is 6,092,674kg. Of the total electricity used in the packhouse, 80% is used by coolstore. This value is $0.8 * 7,978,258 = 6,382,606.4 \text{ kWh}$. According to Table 6, 13% of this total electricity use is associated with avocados = $0.13 * 6,382,606.4 = 829,739\text{kWh}$. Apportioning this to 1kg avocados, we get,	Total avocados stored in the coolstore is 5,505,705 kg. Of the total electricity used in the packhouse, 80% is used by coolstore. This value is $0.8 * 13,500,726 = 10,800,581 \text{ kWh}$. According to Table 6, 6% of this total electricity use is associated with avocados = $0.06 * 10,800,581 = 648,025 \text{ kWh}$. Apportioning this to 1kg avocados, $648,035 /$

		$829,739/6,092,674 = 0.14 \text{ kWh/kg of avocados stored in the coolstore.}$	$5,505,705 = 0.12 \text{ kWh/kg of avocados stored in the coolstore.}$
Post-packaging waste recycling and company transport	Cardboard sent to recycling	Total cardboard packaging (associated with avocados) sent to recycling is 30,000 kg. Therefore, it applies to all avocados packaged (not sent to oil) = 5,206,166 kg. Paring down to 1kg, this quantity is $30000/5,206,166 = 0.006\text{kg/kg of avocados.}$ Transporting the waste cardboard to the recycling centre requires a travel across 15km one way. <u>Therefore, the t.km input = $0.006 * 15/1000 = 0.0001 \text{ t.km}$</u>	Total cardboard packaging (associated with avocados) sent to recycling is 60,644kg. Therefore, it applies to all avocados packaged (not sent to oil) = 5,083,996kg. Paring down to 1kg, this quantity is $60,644 / 5,083,996 = 0.012\text{kg/kg of avocados packed.}$
	Plastic sent to recycling	-	1,906 kg of shrinkwrap sent to recycling. This value is entirely associated with avocado packaging. Therefore, it applies to all avocados packaged (not sent to oil) = 5,083,996kg. Paring down to 1kg, this quantity is $1,906 / 5,083,996 = 0.0004 \text{ kg/kg of avocado packaged.}$ Transporting the waste cardboard and plastic to the recycling centre requires a travel across 15km one way. <u>Therefore, the t.km input = $(0.012+0.0004) * 15/1000 = 0.0002 \text{ t.km / kg of avocados}$</u>
	Company transport	165,000L of diesel for company transport overall. Value associated with avocados is $0.2 * 165,000 = 33,000 \text{ L.}$ Apportioning to 1kg avocados, we get $33,000/6,112,093 = 0.0054\text{L of diesel/kg of avocados.} = 0.005\text{kg diesel (density of diesel is } 860\text{kg/m}^3\text{).}$	13,062 L of diesel for company transport associated with avocados. Paring this down to 1kg avocados, we get $13,062 / 5,548,788 = 0.0024 \text{ L of diesel/kg of avocados.} = 0.0021 \text{ kg diesel / kg of avocad (density of diesel is } 860\text{kg/m}^3\text{).}$ The output of the dataset used is 1km. The dataset shows an input of 0.0766kg

		The dataset we use is 'RER: transport, passenger car, medium size, diesel, EURO 5'. The dataset includes the input of 0.0766kg crude oil for an output of 1km distance travelled. We assume that this is the same as the diesel input. Thus, 0.077 kg diesel is used to travel 1km by passenger car. Therefore, the distance travelled using 0.005 kg diesel $\equiv$ <u>0.065km = 65m.</u>	crude oil for an output of 1km distance travelled. We assume that this is the same as the diesel input. Thus, 0.077 kg diesel is used to travel 1km by passenger car. Therefore, the distance travelled using 0.0021 kg diesel $\equiv$ <u>0.0273km = 27.3m.</u>

Table D34 Product split calculations for electricity and refrigerants used in PH 1

	Storage Weight (kg)	Storage Time (months)	Weight * Time value	Coolstore Electricity (AppORTioned by weight * time)	Packhouse Electricity (AppORTioned by Weight Only)	Refrigerant top-up (AppORTioned by Weight Only)	Comments
Avocado	6,092,854	4.9	29,854,103	13%	20%	20%	See below
Kiwifruit	24,500,000	8.3	203,350,000	87%	80%	80%	
Total	30,592,854	-	-	100%	100%	100%	

Table D35 Product split calculations for electricity and refrigerants used in PH 2

	<u>Storage weight (kg)</u>	<u>Storage Time (months)</u>	<u>Weight * Time value</u>	<u>Coolstore Electricity (AppORTioned by weight * time)</u>	<u>Packhouse Electricity (AppORTioned by Weight Only)</u>	<u>Refrigerant top-up (AppORTioned by Weight Only)</u>	<u>Comments</u>
Avocado	5,505,705	6	33,034,230	6%	8%	8%	See below
Kiwifruit	63,102,906	8.8	557,409,180	94%	92%	92%	

Total	68,608,611	-	590,443,410	100%	100%	100%	

Rationale for Product Split Allocation

The rationale for allocating impact burden shares to coolstore electricity use, and refrigerant use/packline electricity was based on a previous study on the ideal method of allocating GHG s produced by coolstore facilities (East et al., 2010). The study inferred that the most accurate way to allocate impacts from GHGs in coolstores is based on heat load calculations. Heat load could be estimated based on expert judgement, but given this is a significantly more complicated process, the packhouses were not asked for the detailed data on heat load measurements (Andrew Barber, Agrilink, Pers. Comm., 27 April 2022). As such, the next best approach was a combination of mass balance to allocate all packhouse electricity (other than use for cooling purposes) by weight alone, and coolstore electricity by weight multiplied by storage time (months). Refrigerant top up was also allocated by weight alone, since refrigerant leakages occurs even when the system is turned off.

Below is a worked example by Andrew Barber, Agrilink (Pers. Comm., 27 April 2022) to explain the allocation.

Example of allocating coolstore electricity between crops

Packhouse A stores and processes 3,000,000 kg kiwifruit and 500,000 kg of avocados. Their annual electricity use between April 2013 and March 2014 was 1,000,000 kWh. Based on their expert judgement and a previous energy audit they have determined that refrigeration accounts for 80% of the energy used. The rest (20%) is used by lighting, processing, heating and office equipment. The average storage time for kiwi is 3 months and 4 months for avos. Their expert judgement is that 4 kg of avos has the same cooling load as 1 kg of kiwi.

Processing, heating, admin. (mass allocation)

Total (kiwi+avo) = 1,000,000 kWh x 20% = 200,000 kWh.

Kiwifruit only = 200,000 x (3m kg/3.5m kg) = 171,400 kWh (kiwi share based on mass)

Coolstorage (mass and time allocation)

Total (kiwi+avo) = 1,000,000 – 200,000 = 800,000 kWh

Kiwifruit only = 800,000 x 82% (from Table 1 below) = 656,000 kWh

Table D36 Allocation of coolstorage based on mass and time

	<u>Total weight (kg)</u>	<u>Average storage time</u>	<u>Weight months</u>	<u>Share</u>
Kiwifruit	3,000,000	3 months	9,000,000	82%
Avocado	500,000	4 months	2,000,000	18%

Table D37 Allocation of coolstore based on heat load (expert judgement)

	<u>Total weight (kg)</u>	<u>Kiwifruit equivalent weight</u>	<u>Average storage time</u>	<u>Weight x months</u>	<u>Share</u>
Kiwifruit	3,000,000	3,000,000	3 months	9,000,000	95%
Avocado	500,000	125,000 (500,000/4*)	4 month	500,000	5%

* dividing by 4 is based on the packhouse's assumption that 4 kg of avos has the same cooling load as 1 kg of kiwi

Distribution Stage

Packaging weight calculations:

Packhouse 1 weight of packaging per kg avocados for export = $0.004 \text{ (quicklime)} + 0.0201 + 0.1201 + 0.0001 + 0.0001 = 0.144 \text{ kg/kg of avocados}$. Therefore, total weight of 1kg packed avocados = 1.144kg. PH 2 weight of packaging per kg avocados for export = $0.0042 + 0.0959 + 0.105 + 0.0006 + 0.00016 = 0.206 \text{ kg/kg of avocados}$. Therefore, total weight of 1kg packed avocados = 1.206 kg

Packaging weight per kg avocados for exports (single layered trays with pocket packs) – average of PH 1 and 2 = $(0.144 + 0.206)/2 = 0.175$. **Therefore, total weight of 1 kg avocados packaged for export via ship or air is 1.175 kg.**

For domestic transport in crates, the packaging per kg of avocados from PH2 was used as they provided crate usage data. This value is $0.0005 + 0.0001 + 0.0139 = 0.0145 \text{ kg}$. **Therefore, total weight of 1kg avocados packed in crates for the domestic market = 1.0145 kg.**

For domestic transport in bulk boxes without pocket packs, the packaging per kg of avocados from PH1 was used as they provided more representative bulk box packaging data for the local market. This value is: $0.06 + 0.0210 + 0.0002 = 0.0812 \text{ kg}$. **Therefore, total weight of 1kg avocados packed in bulk boxes without pocket packs for the domestic market = 1.0812 kg.**

Distance Calculations:

Avocados are exported from Tauranga and Auckland Port to Brisbane, Melbourne, and Sydney. Therefore, weighted averages for road and rail distances from all the packhouses to both ports were first calculated. These two values were then weighted to obtain the value for the distance travelled to New Zealand ports. The distances to the three Australian ports were then weighted and this became the average distance to Australian Ports. Shipping to South Korea was calculated similarly for weighted average road distances to Tauranga port only since avocados to South Korea by ship are only sent from Tauranga. There was no rail input either, as the fruit from packhouses in the Mid and Far North were only shipped to

Australia. Air freighting to Australia was modelled for weighted averages of the road distances to Auckland airport and then weighted again for the airfreight distances to Brisbane, Melbourne, and Sydney airports to obtain a single input value for airfreighting avocados to Australia. Air freighting to South Korea was modelled only for the weighted average of the road distances to Auckland airport and then the airfreight distance to Incheon. For distribution to the North Island, the weighted average for road transport to nine drop-off points in the north Island was modelled for avocados packaged in plastic crates and bulk loose fill cardboard boxes. The same method was followed for distribution to three drop-off points in the South Island, with the additional distance covered by the ferry trip between the North and South Islands.

Including Plastic Crate (PC) manufacture and end-of-life stages

Table D38 Including Plastic Crate (PC) manufacture and end-of-life stages in single use, and reuse (50 times) scenarios

Impact Category	North island PC	South island PC	North island with plastic whole life	South island with plastic whole life	Plastic whole life % of north island plastic whole life - single use	Plastic whole life % of south island plastic whole life - single use	50 time reuse north island	50 time reuse south island
Climate Change (kg CO ₂ eq./kg avocados)	0.51	0.63	0.6437	0.77	21%	17%	0.4%	0.35%
Eutrophication (kg Phosphate eq./kg avocados)	0.0035	0.0037	0.0043	0.0045	19%	18%	0.39%	0.37%
Water Use (m ³ world equiv./kg avocados)	0.45	0.46	0.5	0.50	7%	7%	0.15%	0.15%
Ecotoxicity (Freshwater) (CTU _e /kg avocados)	7172	7362	7826	8015	8%	8%	0.17%	0.16%
Ecotoxicity (Terrestrial) (kg 1,4-DB eq./kg avocados)	5.50	8.15	5.9	8.5	7%	5%	0.13%	0.09%

Business transport at packhouse

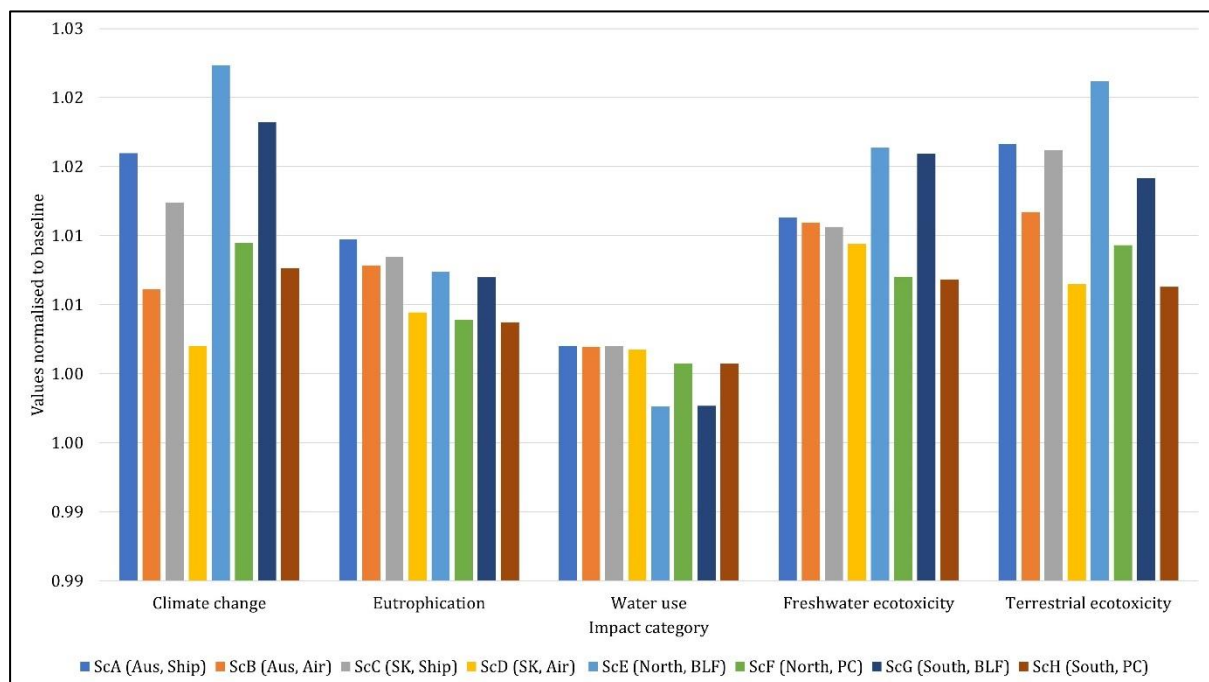


Figure D1 Business transport values normalised to original supply chain scenarios across five impact categories

References

- Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., & Fullana-i-Palmer, P. (2020). When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. *Resources, Conservation and Recycling*, 155, 104666. <https://doi.org/10.1016/j.resconrec.2019.104666>
- European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD) Handbook: General guide for life cycle assessment-detailed guidance*. Publications Office. <https://data.europa.eu/doi/10.2788/38479>
- ISEAL Alliance. (2019). *Introduction to Sustainability Benchmarking: Background information for the ISEAL consultation on good practices in sustainability benchmarking*. ISEAL Alliance. https://www.isealalliance.org/sites/default/files/resource/2019-05/Introduction_to_sustainability_benchmarking-ISEAL-2018.pdf

- Lo-Iacono-Ferreira, V. G., Viñoles-Cebolla, R., Bastante-Ceca, M. J., & Capuz-Rizo, S. F. (2020). Transport of Spanish fruit and vegetables in cardboard boxes: A carbon footprint analysis. *Journal of Cleaner Production*, 244, 118784. <https://doi.org/10.1016/j.jclepro.2019.118784>
- Sazdovski, I., Hauschild, M. Z., Arfelis, S., Bala, A., & Fullana-i-Palmer, P. (2024). Short Communication: Biogenic carbon in fast-moving products: A deception or real contribution to circularity? *Environmental Advances*, 15, 100461. <https://doi.org/10.1016/j.envadv.2023.100461>
- EPD (Environmental Product Declaration) International (2019). Product Category Rules – Fruits and Nuts – Product Category Classification UN CPC 013.
- MfE (Ministry for the Environment) (2020). Measuring Emissions: A Guide for Organizations. 2020 Detailed Guide. Available for download at: Measuring Emissions: Detailed Guide 2020 | Ministry for the Environment
- Mithraratne, N., Barber, A., & McLaren, S. J. (2010). Carbon Footprinting for the Kiwifruit Supply Chain – Report on Methodology and Scoping Study.

Appendix E – Chapter 5

Climate Change Values – Data choices and rationale for calculations

Although a more recent NZ-specific value was available for fresh King salmon (thinkstep-ANZ, 2023), canned pink salmon was used since it is the more commonly consumed option (personal communication with individual consumers). White button mushrooms are the most widely consumed variety of mushrooms in the world (Feeney et al., 2014; Gunady et al., 2012; Robinson et al., 2019), and were therefore chosen for this study. Since most tomato cultivation in NZ occurs in heated greenhouses (TomatoesNZ, 2023), this value was used in this study. Climate change production values for avocado were obtained from a recent study conducted on NZ avocados (Majumdar and McLaren, 2023). Post-harvest packaging and distribution-related climate change impacts were obtained from preliminary results in Majumdar and McLaren (forthcoming). In this LCA study, the post-harvest climate change impacts associated with avocados were determined using packaging data from two major packhouses, and transport data for distribution to several points-of-sale in the North and South Island of NZ. A climate change impact score for NZ-produced milk was available in Drew et al. (2020), which was based on an earlier study (Chobtang, 2016). However, an updated climate change impact value for milk production in NZ (0.76 kg CO₂ eq./kg FPCM⁶², from cradle-to-farm gate, not including Land Use Change or LUC) was published in a more recent report (Mazzetto et al., 2021). This value was used to determine the climate change impact values for Cheddar cheese and butter to reflect current NZ-specific milk production. Using the original FPCM conversion formula provided by International Dairy Federation (2015) – also used by Mazzetto et al. (2021), with average fat and true protein content of 4.83% and 3.76% (table 1, year 2017/18; Ledgard et al., 2020), the climate change impact of milk production used in the current study was calculated at 0.86 kg CO₂ eq./L milk. Assuming that approximately 10 L of milk are needed to produce 1kg Cheddar

⁶² Fat and Protein Corrected Milk (FPCM) is a commonly used FU in dairy LCAs – it serves to standardise milk to a certain concentration of fat and protein (usually 4% and 3.3% respectively)

cheese (Dairy Food Safety Victoria, 2018), the estimated impact associated with milk production is 8.6 kg CO₂ eq./kg cheese. On average, milk production contributes 92% of the climate change impacts of the Cheddar cheese life cycle to the factory gate (Drew et al., 2020, Gosalvittr et al., 2019, and Kim et al., 2013). Therefore, the climate change impact for Cheddar cheese at the factory gate was determined to be 9.3 kg CO₂ eq./kg cheese in NZ. This was only 3% higher than the value listed in Drew et al. (2020), however, it used more recent milk production values specific to NZ, therefore as per the decision tree, this value was used for Cheddar cheese production. The packaging and transport values in Drew et al. (2020) were added to this to provide the final value for use in this study – 9.6 kg CO₂ eq./kg Cheddar cheese. The corresponding value for butter was similarly calculated at 11 kg CO₂ eq./kg butter at the Regional Distribution Centre (RDC) (see supplementary information for table based on decision tree).

One finding from the NZ Nutrition Survey (University of Otago & Ministry of Health; 2011) was that most New Zealanders choose to cook with oil. Therefore, the olive oil climate change impact value was used for the fat required to cook mushrooms, chicken, and bacon rashers. Olive oil climate change impact values were variable in the literature because of disparate system boundaries; therefore, the value in Drew et al. (2020) was used. The climate change impact score for olive oil associated with 1 L of olive oil is 4.7 kg CO₂ eq. Further, the climate change impact associated with energy required to cook mushrooms, chicken, and bacon rashers was also considered and added to the values in the table above⁶³. It was assumed that most people use electric stovetops in NZ, and either pan fry their food or bake it in an oven. It was also assumed for this study that chicken is either baked or pan-fried with oil, while mushroom and bacon rashers are always only pan-fried with oil. Kytä et al. (2023) provided values for cooking-

⁶³ The climate change values obtained from the decision tree analysis for mushrooms, chicken breast, and bacon were associated with uncooked food, whereas eggs, and canned fish were already cooked and this was reflected in their values.

related energy use, based on the study by Frankowska et al. (2020). Kyttä et al. (2023) assumed a cooking time of 15 mins for all food items resulting in energy consumption of 0.54 kWh/kg for pan frying and 0.76 kWh/kg for baking. For the current study, the cooking times were adjusted to 5 minutes and 10 minutes for pan frying mushroom and bacon, and 15 minutes on average for baking or pan-frying chicken. The climate change impact value associated with electricity consumption⁶⁴ (including transmission and distribution) was obtained from the emissions measuring guide published by the Ministry for the Environment (2022).

⁶⁴ It was assumed for this study that all cooking was done on electric stovetops and ovens.

Table E1 An overview of relevant meal-level studies combining nutritional and environmental aspects

Source	Type of meal studied	Parallel or Integrated Study	Method for Nutritional Assessment*	Method for environmental assessment / impact categories included	Combined nutrition-environment ranking
Kägi et al. (2012)	Real-life: Restaurant	Integrated	One meal with different combinations of protein, potatoes, and green beans, adjusted by the NDS and NRF _{9.3} scores	Environmental Footprint using the Eco-indicator 99 and Swiss ecological scarcity methods	Yes
Lukas et al. (2016)	Hypothetical: Classical lunches consumed in Germany	Integrated (average of nutritional and environmental footprint scores)	Three nutritional thresholds representing small, medium, and strong effects determined for energy, sodium, fibre, and saturated fat intake per meal, based on national and international nutritional recommendations/guidelines. Each threshold level assigned a value from 1-3 (1 for small, 2 for medium, and 3 for high impact). Each meal slotted into one of these assigned value categories for each indicator and then the values for the four indicators averaged for an overall 'health' nutritional footprint score.	Environmental thresholds representing small, medium, and strong impacts determined for material, carbon, and water footprints, and land use, based on published literature. Each threshold level assigned a value from 1-3 (1 for small, 2 for medium, and 3 for high impact). Each meal slotted into one of the assigned value categories for each indicator and then the values for the four indicators averaged for an overall 'environmental' footprint score.	Yes
Sturtewagen et al. (2016)	Real life: Worksite canteen	Parallel	Nutritional value calculated based on Belgian food composition tables and the WNDIS nutritional profiling model proposed by Arsenault et al. (2012)	CEENE – an LCA-based approach for resource accounting proposed by Dewulf et al. (2007)	No
Schaubroeck	Real Life:	Parallel	Parameters (for example, protein content)	EF method and CEENE	No

et al. (2018)	Ghent University canteen		and associated recommendations identified based on existing nutritional guidelines. Meals scored per parameter – one penalty point assigned for each parameter which did not meet the criteria in the guidelines. Nutritional score of the meal calculated as the number of nutritional criteria not met + 1.	approach, scores from 1-8 representing smallest to largest impact, assigned to the EF values at intervals.	
Graham et al. (2019)	Real Life: University	Integrated (Statistical co-relation analysis)	Nutritional value obtained for ten nutrients per sandwich portion from the UK Office of Public Sector Information.	GHGE and water footprint scores per sandwich portion combined using orthogonal regression to provide a single environmental impact score.	No
Saxe et al. (2019)	Real-life: Meals catered to senior citizens in Denmark	Integrated	In addition to the mass-based FU, two additional nutrition-based FUs used – energy and protein content.	Global warming and monetized overall environmental impact calculated per meal.	Yes
Batlle-Bayer et al. (2020)	Hypothetical: Spanish tapas meals	Integrated	NRM9.3 based on nine nutrients to encourage and three to limit used in NRF _{9,3}	GWP and BWF	Yes
Cooreman-Algoed et al. (2020)	Real-life: Belgian university canteen	Parallel	WNDS developed by Arsenault et al. (2012). Meals classified nutritionally based on WNDS scores as well as four nutritional threshold values from previous literature.	ReCiPe endpoint single score. Meals classified environmentally based on three reference values – average ReCiPe single score, and the European Commission's GHG reduction targets for 2020 and 2030.	No
Batlle-Bayer et al. (2021)	Real life: School meals in Barcelona	Integrated	NRM _{9,3} based on nine nutrients to encourage and three to limit used in NRF _{9,3}	Water-Energy-Food nexus assessed using BWF, PED, LU, and GWP	Yes

Kluczkowski et al. (2022)	Real Life: School menus	Parallel	Nutritional content of 16 nutrients was calculated using the Brazilian food composition tables, for each individual nutrient per 1000 kcal in conventional and sustainable menus	GHGE calculated for each menu for a school calendar year.	No
Mazac et al. (2023)	Hypothetical: 14 meals adapted from recipe one recipe for a nutritionally balance, low GHGe meal	Integrated	Nutritional footprint method adapted from Lukas et al. (2016); as well as NRF _{24.4} index adapted from Green et al. (2021).	Environmental footprint method adapted from Lukas et al. (2016); as well as the NIEI method, adapted from Green et al. (2021) for the meal context. The environmental impacts were first normalised to the total observed impacts of the European diet for five impact categories (GWP, WU, LU, TA, FE, and ME). The normalised environmental impact scores were then divided by the NRF _{24.4} values to obtain the NIEI values for each impact category. These were then averaged to obtain the NIEI score for each meal.	Yes

* Abbreviations: NDS – Nutrient Density Score; WNDS – Weighted Nutrient Density Score; NRF – Nutrient Rich Food; NRM – Nutrient Rich Meal; EF – Ecological (or Environmental) footprint; CEENE – Cumulative Energy Extraction from the Natural Environment; GHGE (Greenhouse Gas Emissions); GPW – Global Warming Potential; BWF – Blue Water Footprint; PED – Primary Energy Demand; LU – Land Use; NIEI – Nutritionally Invested Environmental Impact; WU – Water Use; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication

Table E2 New Zealand-specific climate change impact scores used in this study for each of the selected toast toppings in the four food groups

Food Group	Chosen Topping*	Climate change impact (kg CO ₂ eq./kg product at first-point-of-domestic sale)**
Vegetables and Fruit	Avocado	0.8
	Banana	0.9
	Mushroom	2.3
	Tomato	2.8
Legumes, nuts, seeds, fish and other seafood, eggs, poultry or red meat with fat removed	Chicken	4.1
	Egg	4.6
	Peanut Butter	1.9
	Salmon (canned, pink)	7.3
	Tuna	5.5
Milk and milk products, mostly low and reduced fat	Cheddar Cheese	10.5
Discretionary foods	Bacon	7.4
	Butter	11.0
	Honey	2.0
	Jam	2.6

* Climate change impact scores for bananas, avocados, eggs, tuna, salmon, and bacon were adjusted to account for the edible portion only (excluding skin, seed, shell, and bones). **All values were consistently calculated for domestic consumption from cradle to the first point of sale (regional distribution centre (RDC) or warehouse), accounting for production of the farmed and/or processed food, consumer packaging, and transport (to the packhouse as well as the first point-of-sale).

Table E3 Serve sizes for the toast toppings, and the source from which they were obtained

Food Group	Topping	New Zealand Food Composition Database (NZFCD) Reference Number	Serve Size	Source for serve sizes	Energy Density (ED) (kcal/serve)
Vegetables and Fruit	Avocado	L1159	85 g	New Zealand Food Composition Database (NZFCD) (2022)	185
	Banana	L1101	111 g	New Zealand Food Composition Database (NZFCD) (2022)	105
	Mushroom	X10010	80 g	New Zealand Food Composition Database (NZFCD) (2022)	58
	Tomato	X1211	80 g	New Zealand Food Composition Database (NZFCD) (2022)	12
Legumes, nuts, seeds, fish and other seafood, eggs, poultry or red meat with fat removed	Chicken	M10040	80 g	Ministry of Health, 2020; National Health and Medical Research Council, 2013	111
	Egg	G1023	50 g	New Zealand Food	90

				Composition Database (NZFCD) (2022)	
	Peanut Butter	Q1019	30 g	Ministry of Health, 2020; National Health and Medical Research Council, 2013	189
	Salmon	K1024	57 g	New Zealand Food Composition Database (NZFCD) (2022)	84
	Tuna*	Average of K1011, K1007, and K1006	70 g	New Zealand Food Composition Database (NZFCD) (2022)	36
Milk and milk products, mostly low and reduced fat	Cheddar cheese	F1015	40 g	New Zealand Food Composition Database (NZFCD) (2022)	168
Discretionary foods	Bacon	N1051	50 g	Ministry of Health, 2020; National Health and Medical Research Council, 2013	188
	Butter**	Average of F1046 and F1050	20 g	Ministry of Health, 2020; National Health and Medical Research Council, 2013	147
	Honey	W1019	21 g	New Zealand Food Composition Database (NZFCD) (2022)	61
	Jam	W14	16 g	New Zealand Food Composition Database (NZFCD) (2022)	47
Cooking oil	Olive Oil***	J10001	5 mL	Based on weight registered on kitchen scale	44

**Average of tuna in brine, assorted oils, and spring water with added salt.*

***Average of salted and unsalted butter.*

****1 serve olive oil added to chicken, egg, and bacon for cooking*

Table E4 List of nutrient indices identified in literature, and their composition

		NR F _{6.3}	NRF 9.3a	NRF _{9.3} b	NRF _{10.} 2	NRF _{11.3} a	NRF 11.3b	NRF 15.3	NRF 20.2	NRF 21.2	NRF 21.2	NR F _{22.} 2	NBC _b	NBC _a	FNI _{pro} t-7	NRF _{ai}	NRF _{protein-} sub
		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Water (L/day)		.	.	.	.	.	.	.	.	.	.	.	.	✓	.	.	.
Carbohydrate		.	.	.	.	.	.	.	.	✓	.	.	.	.	.	.	.
Fibre	Fibre, total dietary	✓	✓	✓	.	✓	✓	✓	.	✓	✓	✓	✓	✓	✓	.	.
Protein and Amino Acids	Protein, total; calculated from total nitrogen	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fats	Long chain PUFA (omega 3 as EPA/DHA)	.	.	.	✓	.	.	.	.	.	.	.	.	.	.	.	.
	Short chain PUFA (omega 3 as alpha linoleic acid or ALA)	.	.	.	.	.	.	.	.	.	.	.	.	✓	.	.	.
	Total omega 3 fatty acids	.	.	.	.	.	.	.	✓	.	✓	✓	.	.	.	.	.
	Short chain PUFA (omega 6 as linolenic acid	.	.	.	✓	.	.	.	.	.	.	.	.	✓	.	.	.
	Total PUFA	.	.	.	.	.	.	.	.	✓	.	.	.	.	✓	.	.
	Total unsaturated fats	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

	MUFAs	.	.	.	.	.	.	✓	.	.		.	.	.	✓	.	.
Minerals	Calcium	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Copper	.	.	.	.	.	.	.	✓	✓		✓	✓	✓	.	.	.
	Iodide	.	.	.	.	.	.	.	✓	.	✓	✓	.	.	.	✓	.
	Iron	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Magnesium	.	✓	✓	.	✓	✓	.	✓	✓	✓	✓	✓	✓	.	✓	.
	Manganese	.	.	.	.	.	.	.	.	✓		.	.	✓	.	.	.
	Phosphorous	.	.	.	✓	.	.	.	✓	✓	✓	✓	✓	✓	.	✓	.
	Potassium	.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.	.	.
	Selenium	.	.	.	.	.	.	.	✓	.	✓	✓	✓	✓	.	✓	.
	Molybdenum	.	.	.	.	.	.	.	.	.	.	.	.	.	.	✓	.
	Zinc	.	.	.	.	✓	.	✓	✓	✓	✓	✓	✓	✓	.	✓	.
Vitamins	Vitamin A (retinol equivalents)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.	✓	.
	Vitamin C (Ascorbic acid)	✓	✓	✓	.	✓	✓	✓	.	✓	✓	✓	✓	✓	.	✓	.
	Vitamin D	.	.	✓	✓	.	✓	✓	✓	.	✓	✓	✓	✓	.	.	.
	Vitamin E	.	✓	.	.	✓	✓	✓	✓	.	✓	✓	✓	✓	.	.	.
	Vitamin K	.	.	.	.	.	.	.	.	.		.	✓	✓	.	.	.
	Choline	.	.	.	.	.	.	.	.	✓		.	✓	✓	.	.	.
	Biotin (Vitamin B7)	.	.	.	.	.	.	.	.	.		.	.	.	.	.	.
	Dietary folate equivalents	.	.	.	.	.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.

	(Vitamin B9)																
	Niacin equivalents, total (Vitamin B3)	.	.	.	.	.	.	.	✓	✓	✓	✓	✓	✓	.	✓	.
	Pantothenic acid (Vitamin B5)	.	.	.	.	.	.	.	.	.		.	.	✓	.	.	.
	Riboflavin (Vitamin B2)	.	.	.	.	.	.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Thiamin (Vitamin B1)	.	.	.	.	.	.	✓	✓	✓	✓	✓	✓	✓	.	✓	.
	Cyanocobalamin (Vitamin B12)	.	.	.	✓	✓	.	✓	✓	✓	✓	✓	✓	✓	.	✓	✓
	Pyridoxal Phosphate or Pyridoxine (Vitamin B6)	.	.	.	.	.	.	.	✓	✓	✓	✓	✓	✓	.	✓	.
.																	
Nutrients to limit	Total fats	.	.	.	.	.	.	.	.	.		.	.	✓	.	.	.
	Saturated fats	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.	.	✓
	Cholesterol	.	.	.	.	.	.	.	.	.		.	.	✓	.	.	.
	Trans Fats	.	.	.	.	.	.	.	.	.		.	.	✓	.	.	.
	Sodium	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	.	.	.
	Total Sugar	.	.	.	.	.	.	.	.	.		.	.	✓	.	.	.
	Free sugars	.	.	.	.	.	.	.	.	.		.	.	.	.	✓	.
	Added Sugar	✓	✓	✓	.	✓	✓	✓	.	.	✓	.	✓	.	.	.	.

Sources in literature: Fulgoni et al. (2009) – NRF_{6.3}, NRF_{9.3}, NRF_{11.3a}, NRF_{15.3}; Strid et al. (2021) – NRF_{11.3b}; Vieux et al. (2013)– NRF_{9.3b}; Avadí and Fréon (2015) – NRF_{10.2}; Ridoutt (2021) – NRF_{ai}; Green et al. (2021) – NRF_{prot-sub}, NRF_{21.2}; Saarinen et al. (2017) – NRF_{prot-7}; McLaren et al. (2021) – NRF_{20.3}; Hallström et al. (2019) – NRF_{20.2}, NRF_{22.2}; Bianchi et al. (2020), Strid et al. (2021) – NRF_{21.3}; Fern et al. (2015), Chaudhary et al. (2018) – NBC_a; Green et al. (2023) – NBC_b

Table E5 Contribution of nutrients common to both indices to the total NR₂₈ score; and top three contributing nutrients to the NR₂₈ score for each of the toppings*

		Contribution (%) of nutrients common to both indices to total NR ₂₈ score	Top three contributing nutrients to NR ₂₈ score
Vegetables and fruit	Avocado	22	MUFAs - 20%; VitB6 and PUFAs - 12% each; Folate - 8%
	Banana	44	Vit B6 - 20%; Vit C - 12%; Potassium - 11%
	Mushroom	16	Riboflavin - 20%; Niacin - 17%; Selenium - 9%
	Tomato	66	Vit C - 34%; Vitamin B6 - 10%; Potassium - 8%
Legumes, nuts, seeds, fish and other seafood, eggs, poultry or red meat with fat removed	Chicken	23	Niacin - 26%; MUFAs - 11%; Selenium and Protein each - 10%
	Egg	18	MUFAs - 18%; Vitamin E and PUFAs each - 9%; Selenium - 7%
	Peanut Butter	28	MUFAs - 18%; Niacin - 15%; PUFAs - 11%
	Salmon	11	VitB12 - 24%; Vitamin D - 21%; PUFAs - 13%
	Tuna	11	VitB12 - 21%; Selenium - 19%; Niacin - 17%
Milk and milk products	Cheddar cheese	37	Calcium - 15%; Phosphorous - 11%; Vitamin A and Protein - 9% each
Discretionary foods	Bacon	19	MUFAs - 22%; PUFAs and Niacin each - 13%; Protein - 9%
	Butter	30	Vitamin A - 23%; MUFAs and PUFAs each - 22%; Vit D - 13%
	Honey	15	Riboflavin - 50%; Vitamin B6 - 14%; Manganese - 13%
	Jam	63	Vit C - 26%; Manganese - 20%; Fibre - 14%

* Values in red indicate toppings which showed lower NR₂₈ scores compared with NR₉; Values in brown are nutrients common to both indices

Table E6 Change in ranking* from Ranking set A to B for each of the three FUs

Food Group	Topping	Change in ranking Scenario A to B per serve size	Change in ranking Scenario A to B per 100 g	Change in ranking Scenario A to B per 100 kcal
Vegetables and fruit	Avocado	↑	-	-
	Banana	↓	↓↓	↓
	Mushroom	-	↑	-
	Tomato	↓↓	↓↓	-
Legumes, nuts, seeds, fish and other seafood, eggs, poultry or red meat with fat removed	Chicken	-	-	↓
	Egg	↑	-	-
	Peanut Butter	↓	-	↓
	Salmon	↑	-	-
	Tuna	↑	↑	↑
Milk and milk products, mostly low and reduced fat	Cheddar Cheese	-	-	-
Discretionary foods	Bacon	-	↑	↑
	Butter	-	↑	-
	Honey	-	-	-
	Jam	-	-	-

* Number of arrows denotes number of ranks moved up or down

Table E7 Climate change impact of selected toppings in the ToTs meal, based on different production methods

Food Product	Different Production Systems	Climate Change impact (kg CO ₂ eq./kg product)	References
Tomatoes	Greenhouse – actively heated	0.07-2.5	(Almeida et al., 2014; Clune et al., 2017; Dias et al., 2017; Khoshnevisan et al., 2014; Naseer et al., 2022; Urbano et al., 2022; Zarei et al., 2019)
	Greenhouse – passively heated	0.03-0.9	(Bojacá et al., 2014; Canaj et al., 2020; Clune et al., 2017; Payen et al., 2015; Solimene et al., 2023; Urbano et al., 2022)
	Open field	0.02-0.3	(Clune et al., 2017; Scuderi et al., 2023; Urbano et al., 2022; Zarei et al., 2019)
Eggs	Caged – Battery/conventional cage; Enriched cages (also called colony cages)	2.4-2.9	(Guillaume et al., 2022; Leinonen & Kyriazakis, 2016; Turner et al., 2022; Pelletier, 2017)
	Barn (free run)	2.8-3.5	(Li et al., 2021; Guillaume et al., 2022; Leinonen and Kyriazakis, 2016; Turner et al., 2022; Pelletier, 2017)
	Free range	2.4-3.4	Guillaume et al., 2022; Leinonen and Kyriazakis, 2016; Turner et al., 2022; Pelletier, 2017)
	Organic	1.3-3.5	Guillaume et al., 2022; Leinonen and Kyriazakis, 2016; Turner et al., 2022; Pelletier, 2017)
Jam	Fresh fruit	1.2	Boenzi et al. (2022); Digiesi et al. (2022)
	Semi-finished – deep freeze	3.5	Boenzi et al. (2022)
	Semi-finished – ohmic aseptic treatment	3.0	Boenzi et al. (2022)
	Semi-finished – LPSSD-FIR*	2.8	Boenzi et al. (2022); Digiesi et al. (2022)
Honey	Migratory farms	1.9-2.5	Pignagnoli et al. (2021, 2023)
	Stationary farms	0.42-0.58	Pignagnoli et al. (2021, 2023)
Salmon	Farmed	2.15-6.4	Pelletier et al. (2009); Philis et al. (2019)
	Wild capture	0.8-1.2	Ziegler and Hilborn (2023)

* LPSSD-FIR stands Low-Pressure Superheated Steam Drying with Far-Infrared Radiation

Table E8 Quantity of nutrients per serve of NZ-grown avocados (85 g) for two harvesting periods – early (September) and late (April) (Source: New Zealand Food Composition Database (NZFCD), 2022)

Nutrient	Unit	Early season (September) avocados	Late season (April) avocados	Change from early to late season (%)
Dietary Fibre	g	3.4	5.4	59 ↑
Energy	Kcal	152	218	43 ↑
MUFAs	g	10.3	15	46 ↑
PUFAs	g	1.6	3.6	125 ↑
Saturated fats	g	2.2	3.4	54 ↑
Calcium	mg	9	7	22 ↓

Iodine	µg	0	1.3	130 ↑
Iron	mg	0	0.7	70 ↑
Manganese	µg	162	136	16 ↓
Phosphorous	mg	40	37	7.5 ↓
Potassium	mg	374	510	36 ↑
Sodium	mg	11	8	18 ↑
Zinc	mg	0.4	0.6	50 ↑
Protein	g	1.3	1.7	31 ↑
Folate	µg	85	102	20 ↑
Niacin	mg	1.9	2.2	16 ↑
Pantothenic acid	mg	0.7	0.8	14 ↑
Vitamin B6	mg	0.5	0.6	20 ↑
Vitamin C	mg	3	1.6	47 ↓
Vitamin A	µg	7	5	29 ↓
Vitamin K	µg	7.4	4.2	43 ↓
Water	g	63	52	17 ↓

References

- Almeida, J., Achten, W. M. J., Verbist, B., Heuts, R. F., Schrevens, E., & Muys, B. (2014). Carbon and Water Footprints and Energy Use of Greenhouse Tomato Production in Northern Italy. *Journal of Industrial Ecology*, 18(6), 898–908. <https://doi.org/10.1111/jiec.12169>
- Avadí, A., & Fréon, P. (2015). A set of sustainability performance indicators for seafood: Direct human consumption products from Peruvian anchoveta fisheries and freshwater aquaculture. *Ecological Indicators*, 48, 518–532. <https://doi.org/10.1016/j.ecolind.2014.09.006>
- Battle-Bayer, L., Aldaco, R., Bala, A., & Fullana-i-Palmer, P. (2020). Toward sustainable dietary patterns under a water–energy–food nexus life cycle thinking approach. *Current Opinion in Environmental Science & Health*, 13, 61–67. <https://doi.org/10.1016/j.coesh.2019.11.001>
- Battle-Bayer, L., Bala, A., Aldaco, R., Vidal-Monés, B., Colomé, R., & Fullana-i-Palmer, P. (2021). An explorative assessment of environmental and nutritional benefits of introducing low-carbon meals to Barcelona schools. *Science of The Total Environment*, 756, 143879. <https://doi.org/10.1016/j.scitotenv.2020.143879>
- Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U., & Hallström, E. (2020). Systematic Evaluation of Nutrition Indicators for Use within Food LCA Studies. *Sustainability*, 12(21), Article 21. <https://doi.org/10.3390/su12218992>
- Boenzi, F., Digiesi, S., Facchini, F., & Silvestri, B. (2022). Life Cycle Assessment in the Agri-Food Supply Chain: Fresh Versus Semi-Finished Based Production Process. *Sustainability*, 14(20), 13010. <https://doi.org/10.3390/su142013010>

- Bojacá, C. R., Wyckhuys, K. A. G., & Schrevels, E. (2014). Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. *Journal of Cleaner Production*, 69, 26–33. <https://doi.org/10.1016/j.jclepro.2014.01.078>
- Canaj, K., Mehmeti, A., Cantore, V., & Todorović, M. (2020). LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study. *Environmental Science and Pollution Research*, 27(7), 6960–6970. <https://doi.org/10.1007/s11356-019-07191-7>
- Chaudhary, A., Marinangeli, C. P. F., Tremorin, D., & Mathys, A. (2018). Nutritional Combined Greenhouse Gas Life Cycle Analysis for Incorporating Canadian Yellow Pea into Cereal-Based Food Products. *Nutrients*, 10(4). <https://doi.org/10.3390/nu10040490>
- Chobtang, J. (2016). *Appraisal of the environmental sustainability of milk production systems in New Zealand*.
- Clune, S., Crossin, E., & Verghese, K. (2017). Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, 140, 766–783. <https://doi.org/10.1016/j.jclepro.2016.04.082>
- Cooreman-Algoed, M., Huysveld, S., Lachat, C., & Dewulf, J. (2020). How to integrate nutritional recommendations and environmental policy targets at the meal level: A university canteen example. *Sustainable Production and Consumption*, 21, 120–131. <https://doi.org/10.1016/j.spc.2019.10.004>
- Dairy Food Safety Victoria. (2018). *Regulating Victoria's dairy industry—Cheese*. <https://www.dairysafe.vic.gov.au/consumers/dairy-foods/cheese>
- Dias, G. M., Ayer, N. W., Khosla, S., Van Acker, R., Young, S. B., Whitney, S., & Hendricks, P. (2017). Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. *Journal of Cleaner Production*, 140, 831–839. <https://doi.org/10.1016/j.jclepro.2016.06.039>
- Digiesi, S., Facchini, F., & Silvestri, B. (2022). Green strategies to reduce the environmental impact of jam production. *Transportation Research Procedia*, 67, 72–82. <https://doi.org/10.1016/j.trpro.2022.12.037>
- Drew, J., Cleghorn, C., Macmillan, A., & Mizdrak, A. (2020). Healthy and Climate-Friendly Eating Patterns in the New Zealand Context. *Environmental Health Perspectives*, 128(1), 017007. <https://doi.org/10.1289/EHP5996>

- Feeney, M. J., Miller, A. M., & Roupas, P. (2014). Mushrooms—Biologically Distinct and Nutritionally Unique. *Nutrition Today*, 49(6), 301–307.
<https://doi.org/10.1097/NT.0000000000000063>
- Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A., & Drewnowski, A. (2015). The Nutrient Balance Concept: A New Quality Metric for Composite Meals and Diets. *PLOS ONE*, 10(7), e0130491.
<https://doi.org/10.1371/journal.pone.0130491>
- Frankowska, A., Rivera, X. S., Bridle, S., Kluczkowski, A. M. R. G., Tereza da Silva, J., Martins, C. A., Rauber, F., Levy, R. B., Cook, J., & Reynolds, C. (2020). Impacts of home cooking methods and appliances on the GHG emissions of food. *Nature Food*, 1(12), Article 12.
<https://doi.org/10.1038/s43016-020-00200-w>
- Fulgoni, V. L. I., Keast, D. R., & Drewnowski, A. (2009). Development and Validation of the Nutrient-Rich Foods Index: A Tool to Measure Nutritional Quality of Foods. *The Journal of Nutrition*, 139(8), 1549–1554. <https://doi.org/10.3945/jn.108.101360>
- Gosalvitir, P., Cuellar-Franca, R., Smith, R., & Azapagic, A. (2019). Energy demand and carbon footprint of cheddar cheese with energy recovery from cheese whey. *Energy Procedia*, 161, 10–16. <https://doi.org/10.1016/j.egypro.2019.02.052>
- Graham, F., Russell, J., Holdsworth, M., Menon, M., & Barker, M. (2019). Exploring the Relationship between Environmental Impact and Nutrient Content of Sandwiches and Beverages Available in Cafés in a UK University. *Sustainability*, 11(11), Article 11.
<https://doi.org/10.3390/su11113190>
- Green, A., Nemecek, T., & Mathys, A. (2023). A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: The metrics and their assumptions matter. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02210-9>
- Green, A., Nemecek, T., Smetana, S., & Mathys, A. (2021). Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *Journal of Cleaner Production*, 312, 127696.
<https://doi.org/10.1016/j.jclepro.2021.127696>
- Guillaume, A., Hubatová-Vacková, A., & Kočí, V. (2022). Environmental Impacts of Egg Production from a Life Cycle Perspective. *Agriculture*, 12(3), Article 3.
<https://doi.org/10.3390/agriculture12030355>

- Gunady, M. G. A., Biswas, W., Solah, V. A., & James, A. P. (2012). Evaluating the global warming potential of the fresh produce supply chain for strawberries, romaine/cos lettuces (*Lactuca sativa*), and button mushrooms (*Agaricus bisporus*) in Western Australia using life cycle assessment (LCA). *Journal of Cleaner Production*, 28, 81–87.
<https://doi.org/10.1016/j.jclepro.2011.12.031>
- Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., & Ziegler, F. (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production*, 230, 402–411. <https://doi.org/10.1016/j.jclepro.2019.04.229>
- Kägi, T., Zschokke, M., & Dinkel, F. (2012, October 2). *Nutrient based functional unit for meals*. 8th International Conference on LCA in the Agri-Food Sector, Rennes, France.
<https://doi.org/10.13140/RG.2.1.1689.7367>
- Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., & Clark, S. (2014). Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. *Journal of Cleaner Production*, 73, 183–192.
<https://doi.org/10.1016/j.jclepro.2013.09.057>
- Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., & Norris, G. (2013). Life cycle assessment of cheese and whey production in the USA. *The International Journal of Life Cycle Assessment*, 18(5), 1019–1035. <https://doi.org/10.1007/s11367-013-0553-9>
- Kluczkowski, A., Menezes, C. A., da Silva, J. T., Bastos, L., Lait, R., Cook, J., Cruz, B., Cerqueira, B., Lago, R. M. R. S., Gomes, A. N., Ladeia, A. M. T., Schmidt Rivera, X., Vianna, N., Reynolds, C. J., Oliveira, R. R., & Bridle, S. L. (2022). An Environmental and Nutritional Evaluation of School Food Menus in Bahia, Brazil That Contribute to Local Public Policy to Promote Sustainability. *Nutrients*, 14(7), Article 7. <https://doi.org/10.3390/nu14071519>
- Kyttä, V., Kårlund, A., Pellinen, T., Pietiläinen, O., Tuomisto, H. L., Kolehmainen, M., Pajari, A.-M., & Saarinen, M. (2023). Product-group-specific nutrient index as a nutritional functional unit for the Life Cycle Assessment of protein-rich foods. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-023-02217-2>
- Ledgard, S. F., Falconer, S. J., Abercrombie, R., Philip, G., & Hill, J. P. (2020). Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. *Journal of Dairy Science*, 103(1), 1031–1046. <https://doi.org/10.3168/jds.2019-17182>
- Leinonen, I., & Kyriazakis, I. (2016). How can we improve the environmental sustainability of poultry production? *The Proceedings of the Nutrition Society*, 75(3), 265–273.
<https://doi.org/10.1017/S0029665116000094>

- Li, Y., Allacker, K., Feng, H., Heidari, M. D., & Pelletier, N. (2021). Net zero energy barns for industrial egg production: An effective sustainable intensification strategy? *Journal of Cleaner Production*, 316, 128014. <https://doi.org/10.1016/j.jclepro.2021.128014>
- Lukas, M., Rohn, H., Lettenmeier, M., Liedtke, C., & Wiesen, K. (2016). The nutritional footprint – integrated methodology using environmental and health indicators to indicate potential for absolute reduction of natural resource use in the field of food and nutrition. *Journal of Cleaner Production*, 132, 161–170. <https://doi.org/10.1016/j.jclepro.2015.02.070>
- Majumdar, S., & McLaren, S. J. (2023). Towards use of life cycle–based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand. *The International Journal of Life Cycle Assessment*, 29, 192–217. <https://doi.org/10.1007/s11367-023-02238-x>
- Mazac, R., Järviö, N., & Tuomisto, H. L. (2023). Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. *Science of The Total Environment*, 876, 162796. <https://doi.org/10.1016/j.scitotenv.2023.162796>
- Mazzetto, A., Falconer, S., & Ledgard, S. (2021). *Updating the carbon footprint for selected New Zealand agricultural products an update for milk.*
- McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., De Camillis, C., Renouf, M., Rugani, B., Saarinen, M., van der Pols, J., Vázquez-Rowe, I., Vallejo, A. A., Bianchi, M., Chaudhary, A., Chen, C., Cooreman-Algoed, M., Dong, H., Grant, T., ... van Zanten, H. (2021). *Integration of environment and nutrition in life cycle assessment of food Items: Opportunities and challenges.* <https://doi.org/10.4060/cb8054en>
- Ministry for the Environment. (2022). *New Zealand Greenhouse Gas Inventory 2022.*
- Ministry of Health. (2020). *Eating and Activity Guidelines for New Zealand Adults—2020.*
- Naseer, M., Persson, T., Hjelkrem, A.-G. R., Ruoff, P., & Verheul, M. J. (2022). Life cycle assessment of tomato production for different production strategies in Norway. *Journal of Cleaner Production*, 372, 133659. <https://doi.org/10.1016/j.jclepro.2022.133659>
- National Health and Medical Research Council. (2013). *Educator guide—Information for nutrition educators.* https://www.eatforhealth.gov.au/sites/default/files/files/the_guidelines/n55b_eat_for_health_educators_guide.pdf
- New Zealand Food Composition Database (NZFCD). (2022). *Search for a Food—New Zealand Food Composition Database.* <https://www.foodcomposition.co.nz/search/food>

- Payen, S., Basset-Mens, C., & Perret, S. (2015). LCA of local and imported tomato: An energy and water trade-off. *Journal of Cleaner Production*, 87, 139–148.
<https://doi.org/10.1016/j.jclepro.2014.10.007>
- Pelletier, N. (2017). Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. *Journal of Cleaner Production*, 152, 167–180.
<https://doi.org/10.1016/j.jclepro.2017.03.050>
- Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., & Silverman, H. (2009). Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. *Environmental Science & Technology*, 43(23), 8730–8736.
<https://doi.org/10.1021/es9010114>
- Philis, G., Ziegler, F., Gansel, L. C., Jansen, M. D., Gracey, E. O., & Stene, A. (2019). Comparing Life Cycle Assessment (LCA) of Salmonid Aquaculture Production Systems: Status and Perspectives. *Sustainability*, 11(9), Article 9. <https://doi.org/10.3390/su11092517>
- Pignagnoli, A., Pignedoli, S., Carpana, E., Costa, C., & Dal Prà, A. (2021). Carbon Footprint of Honey in Different Beekeeping Systems. *Sustainability*, 13(19), Article 19.
<https://doi.org/10.3390/su131911063>
- Pignagnoli, A., Pignedoli, S., Carpana, E., Costa, C., & Dal Prà, A. (2023). Greenhouse Gas (GHG) Emissions from Honey Production: Two-Year Survey in Italian Beekeeping Farms. *Animals*, 13(4), Article 4. <https://doi.org/10.3390/ani13040766>
- Ridoutt, B. (2021). Bringing nutrition and life cycle assessment together (nutritional LCA): Opportunities and risks. *The International Journal of Life Cycle Assessment*, 26(10), 1932–1936. <https://doi.org/10.1007/s11367-021-01982-2>
- Robinson, B., Winans, K., Kendall, A., Dlott, J., & Dlott, F. (2019). A life cycle assessment of Agaricus bisporus mushroom production in the USA. *The International Journal of Life Cycle Assessment*, 24(3), 456–467. <https://doi.org/10.1007/s11367-018-1456-6>
- Saarinen, M., Fogelholm, M., Tahvonen, R., & Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *Journal of Cleaner Production*, 149, 828–844. <https://doi.org/10.1016/j.jclepro.2017.02.062>
- Saxe, H., Jensen, J. D., Bølling Laugesen, S. M., & Bredie, W. L. P. (2019). Environmental impact of meal service catering for dependent senior citizens in Danish municipalities. *The International Journal of Life Cycle Assessment*, 24(4), 654–666.
<https://doi.org/10.1007/s11367-018-1487-z>

- Schaubroeck, T., Ceuppens, S., Luong, A. D., Benetto, E., De Meester, S., Lachat, C., & Uyttendaele, M. (2018). A pragmatic framework to score and inform about the environmental sustainability and nutritional profile of canteen meals, a case study on a university canteen. *Journal of Cleaner Production*, 187, 672–686. <https://doi.org/10.1016/j.jclepro.2018.03.265>
- Scuderi, A., Timpanaro, G., & Cammarata, M. (2023). Analysis of global warming potential: Organic vs. Conventional tomatoes. *Agricultural Economics (Zemědělská Ekonomika)*, 69(7), 267–275. <https://doi.org/10.17221/104/2023-AGRICECON>
- Solimene, S., Coluccia, D., & Bernardo, A. (2023). Environmental Impact of Different Business Models: An LCA Study of Fresh Tomato Production in Italy. *Sustainability*, 15(13), Article 13. <https://doi.org/10.3390/su151310365>
- Strid, A., Hallström, E., Sonesson, U., Sjons, J., Winkvist, A., & Bianchi, M. (2021). Sustainability Indicators for Foods Benefiting Climate and Health. *Sustainability*, 13(7), Article 7. <https://doi.org/10.3390/su13073621>
- Sturtewagen, L., De Soete, W., Dewulf, J., Lachat, C., Lauryssen, S., Heirman, B., Rossi, F., & Schaubroeck, T. (2016). Resource use profile and nutritional value assessment of a typical Belgian meal, catered or home cooked, with pork or Quorn™ as protein source. *Journal of Cleaner Production*, 112, 196–204. <https://doi.org/10.1016/j.jclepro.2015.09.006>
- TomatoesNZ. (2023). *Industry Overview—Tomatoes*. Tomatoesnz. <https://www.tomatoesnz.co.nz/industry/industry-overview/>
- Turner, I., Heidari, D., & Pelletier, N. (2022). Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: Update and analysis of trends and conditions. *Resources, Conservation and Recycling*, 176, 105907. <https://doi.org/10.1016/j.resconrec.2021.105907>
- University of Otago, & Ministry of Health. (2011). *A focus on nutrition: Key findings of the 2008/09 New Zealand Adult Nutrition Survey*.
- Urbano, B., Barquero, M., & González-Andrés, F. (2022). The environmental impact of fresh tomatoes consumed in cities: A comparative LCA of long-distance transportation and local production. *Scientia Horticulturae*, 301, 111126. <https://doi.org/10.1016/j.scienta.2022.111126>
- Vieux, F., Soler, L.-G., Touazi, D., & Darmon, N. (2013). High nutritional quality is not associated with low greenhouse gas emissions in self-selected diets of French adults. *The American Journal of Clinical Nutrition*, 97(3), 569–583. <https://doi.org/10.3945/ajcn.112.035105>

- Zarei, M. J., Kazemi, N., & Marzban, A. (2019). Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. *Journal of the Saudi Society of Agricultural Sciences*, 18(3), 249–255. <https://doi.org/10.1016/j.jssas.2017.07.001>
- Ziegler, F., & Hilborn, R. (2023). Fished or farmed: Life cycle impacts of salmon consumer decisions and opportunities for reducing impacts. *Science of The Total Environment*, 854, 158591. <https://doi.org/10.1016/j.scitotenv.2022.158591>

Appendix F – Statements of Contribution

 MASSEY UNIVERSITY TE KUNHUA RI PŪREHUOKA UNIVERSITY OF NEW ZEALAND		GRADUATE RESEARCH SCHOOL	
STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS			
We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Shreyasi Majumdar		
Name and title of main supervisor:	Prof. Sarah J. McLaren		
In which chapter is the manuscript/published work?	Chapter 2		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ The candidate was responsible for conceptualization, method development, data collection, analysis, and writing the manuscript. The supervisory team supported the candidate in conceptualization and method development, and editing early versions of the manuscript.			
Please select one of the following three options:			
☐ The manuscript/published work is published or in press Please provide the full reference of the research output:			
☐ The manuscript is currently under review for publication Please provide the name of the journal:			
☒ It is intended that the manuscript will be published, but it has not yet been submitted to a journal			
Student's signature:	Shreyasi Majumdar Digitally signed by Shreyasi Majumdar DN: cn=Shreyasi Majumdar, o=Massey University, ou=New Zealand Life Cycle Management (NZLCLM) Centre email=shreyasi.majumdar@massey.ac.nz Reason: I have reviewed this document Date: 2025.07.29 16:02:08 +0800	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2025.08.21 13:31:21 +12'00'
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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name: Shreyasi Majumdar

Name and title of main supervisor: Prof Sarah J. McLaren

In which chapter is the manuscript/published work? Chapter 3

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:¹

The candidate led the research conceptualization, method development, data collection, performing the LCA, data analysis, and writing the manuscript. Prof Sarah McLaren advised on method development and data collection, interpreting the results, and editing the manuscript.

Please select one of the following three options:



The manuscript/published work is published or in press

Please provide the full reference of the research output:

Majumdar, S., & McLaren, S.J. (2023). Towards use of life cycle-based indicators to support continuous improvement in the environmental performance of avocado orchards in New Zealand. The International Journal of Life Cycle Assessment. 29, 192-217. <https://doi.org/10.1007/s11367-023-02238-x>



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It is intended that the manuscript will be published, but it has not yet been submitted to a journal

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Student name:	Shreyasi Majumdar
Name and title of main supervisor:	Prof. Sarah J. McLaren

In which chapter is the manuscript/published work? **Chapter 4**

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:¹

The candidate was responsible for research collaboration and conceptualization, method development, data collection, performing the LCA study, data analysis and interpretation, and writing the manuscript. The supervisory team was involved in method development, data interpretation, editing the manuscript and supervising the overall project.

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Student's signature:	Shreyasi Majumdar	Digitally signed by Shreyasi Majumdar DN: cn=Shreyasi Majumdar, o=Massey University, ou=Office of Student Life Cycle Management 2025.08.25 email=smajumdar@massey.ac.nz Reason: I have reviewed this document. Date: 2025.07.25 15:15:00 +12'00'	Main supervisor's signature:	Sarah McLaren	Digitally signed by Sarah McLaren Date: 2025.08.25 17:34:36 +12'00'

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We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name: Shreyasi Majumdar

Name and title of main supervisor: Prof. Sarah J. McLaren

In which chapter is the manuscript/published work? Chapter 5

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:¹

The candidate led conceptualization of the research idea, the literature review, method development, data collection, analysis and interpretation, and writing the manuscript. The co-authors provided guidance regarding conceptualization of the research, method development and sourcing of data, and editing the manuscript.

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Please provide the full reference of the research output:

Majumdar, S., McLaren S.J., van der Pols, J.C., and Lister, C.E. (2024). An nLCA approach to support consumer meal decisions: a New Zealand case study of toppings on toast. *Frontiers in Sustainable Food Systems*. 8:1363565. <https://doi.org/10.3389/fsufs.2024.1363565>



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