Ministry for Primary Industries
Manatū Ahu Matua

Research review – Assessing and modelling the environmental performance of horticultural land uses

June 2023

Te Kāwanatanga o Aotearoa
New Zealand Government

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Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: Stats_Info@mpi.govt.nz

PFR SPTS No. 23816

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Hu W, Clothier B, Brown H, Thomas S, Sharp J, Searle B

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Ministry for Primary Industries

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PUBLICATION DATA

Hu W, Clothier B, Brown H, Thomas S, Sharp J, Searle B. June 2023. Assessing and modelling the environmental performance of horticultural land uses. A Plant & Food Research report prepared for: Ministry for Primary Industries. Milestone No. 95212. Contract No. 40502. Job code: P/441041/01. PFR SPTS No. 23816.

KEYWORDS: Water use, water quality, soil health, biodiversity, greenhouse gas emissions, disease management, heavy metal, risk matrix, key performance indicator, models.

Report prepared by:

Wei Hu
Scientist, Soil Function & Health
June 2023

Report approved by:

Penny Tricker
Science Group Leader, Cropping Systems & Environment
June 2023

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Assessing and modelling the environmental performance of horticultural land uses

Hu W[1], Clothier B[2], Brown H[1], Thomas S[1], Sharp J[1], Searle B[3]
Plant & Food Research: [1]Lincoln, [2]Palmerston North, [3]Hawke's Bay

June 2023

Continual improvement of environmental performance is crucial to achieving sustainable development and growth in New Zealand horticulture. This literature review was conducted to help identify and understand: (1) The environmental metrics, relevant data, and development of risk matrices and key performance indicators (KPIs) to help assess the environmental performance of horticulture farms, orchards, and vineyards; and (2) Relevant tools and models for horticulture environmental data and scenario analyses.

The key findings and insights are summarised below:

Environmental performance assessment using environmental metrics, risk matrices, and key performance indicators (KPIs)

A comprehensive literature search was undertaken to review the environmental areas of interest and environmental performance assessment in the horticultural sector. Water quantity and quality, soil health, biodiversity, greenhouse gas emissions, weed, pest and disease management, and heavy metals are the main environmental issues in horticulture. The exact environmental issues in horticulture may differ by crop, and prioritising specific environmental metrics for data collection is necessary to avoid costly and impractical assessments.

Quantification of water use and loss on an annual and seasonal basis is important for characterising the potential impacts of water use, and irrigation systems and water conservation measures should also be assessed. Understanding the key sources of contaminants, such as nitrogen, phosphorous, pesticides, sediment, and untreated discharge from indoor growing systems, is vital for assessing and prioritising water quality in horticultural land uses.

Soil health is crucial for crop yield, quality, and environmental performance, and an ecosystem services-oriented approach should be used to characterise soil health in horticulture land uses. Biodiversity is crucial for supporting ecosystem services and can be assessed in agricultural settings by studying aquatic ecosystems on farms. Understanding and monitoring local ecosystems, along with conservation efforts, are essential for protecting habitats, sustaining ecosystem services, and restoring key species.

Accounting-based models are widely used to estimate greenhouse gas emissions. However, other nitrogen inputs such as residue return and the interactions with environmental factors (e.g. soil compaction) have not been taken into account in approved greenhouse gas emissions tools. In addition, the ability to quantify carbon sequestration is not yet available.

Integrated management systems that combine chemical, biological, and cultural methods are increasingly being used to manage weeds, pests, and diseases. Metrics and attributes for measuring weed, pest, and disease management at a farm level mainly include the number of sprays, type of spray, area sprayed, spray rate, and spray efficiency. However, environmental performance and impacts are difficult to quantify and require further exploration. Heavy metals can be present in horticultural soils and products, posing risks to human health and the environment, and guidelines and regulations are in place to monitor and manage their concentrations. The Ministry for Primary Industries (MPI) in New Zealand sets maximum concentrations for heavy metals in soil and water, and growers must regularly test to comply.

The traditional Māori practices of managing and utilising natural resources, known as mahinga kai, are interconnected with Tikanga Māori principles that guide sustainable practices in a respectful and balanced manner. It is crucial to protect and enhance mahinga kai for sustainable environmental management, access to clean and healthy food, and securing food sustainably. It is noted that in instances where land use consents are required, growers have a responsibility to address mahinga kai. Further research is needed to understand the effect of horticultural activities on water quality and mahinga kai.

Efforts, supported by New Zealand's Ministry for the Environment (MfE), are underway to develop a robust risk matrix for evaluating environmental issues like nitrogen loss. The risk matrix should consider system components (e.g. soil, climate and topography) and exposure (e.g. management practices), assess mitigation requirements for management practices, and account for trade-offs between nitrogen leaching and surface runoff. Expert knowledge or modelling can help determine the final score of nitrogen loss risk for a cropping system.

The development of KPIs has been a focus for assessing environmental performance alongside other aspects of sustainability, such as production and social wellbeing. Three groups of KPIs have been categorised: resource use efficiency-based, environmental footprint-based, and eco-efficiency-based. However, most KPIs, such as resource use efficiency and environmental footprint, can only be used to assess one environmental topic, such as greenhouse gas emissions, along with one outcome, such as production. This is because different environmental performances are difficult to integrate as one value. To fully understand and compare different growing systems for the same crop or different crops in terms of sustainability, it is necessary to have a comprehensive understanding of all key environmental issues. In this regard, data envelopment analysis (DEA) in combination with life cycle assessment (LCA) can be a promising tool. DEA can help to identify the most efficient decision-making units (DMUs) and provide benchmarks for less efficient DMUs to improve their environmental performance. LCA can provide a comprehensive understanding of the environmental impacts associated with a product or system, including its resource use, emissions, and waste generation. By combining DEA and LCA, it is possible to identify the most efficient growing systems in terms of sustainability by considering all key environmental issues. This can help guide decision-making and encourage the adoption of more sustainable practices in agriculture.

Models to assess environmental performance

Simple models can be used to record grower activities and farm system characteristics to assess potential benefits or harm to the environment, but they may not provide a clear picture of overall environmental performance. More detailed approaches involve quantifying farm outputs through existing or additional data collection and using models to predict outputs that are not practical to measure in non-research contexts. Seven categories of models can be classified. They are: farm scale accounting models, basic farm models, deterministic farm system models, single crop decision support systems, detailed process models, catchment erosion/sediment models, and digital farm shadow. Each category has its own characteristics, and the accessibility of the models depends on the expertise of the operator. It is important to have skilled operators to ensure that input data and configurations are defensible and that the results produced are valid.

In New Zealand, the most commonly used environmental models are Overseer, APSIM and SPASMO. Overseer is a basic farm model used to model the nitrogen, carbon, and water balances of different farm types in New Zealand. It takes inputs of climate, soil, and management practices to predict nutrient losses, greenhouse gas emissions, and water balance variables. Overseer is available through subscription and has been criticised for its lack of confidence in predicting nitrogen loss to waterways. APSIM is a widely used deterministic farm systems model that predicts nitrogen leaching, denitrification, and soil carbon losses/sequestration. It has a flexible approach to specifying management and making custom calculations during runtime. Inputs required include climate, soil, and management information. Outputs include irrigation and fertiliser applications, drainage, runoff, leaching, soil moisture content, crop nitrogen uptake, transpiration, evaporation, denitrification, mineralisation, soil carbon, and soil nitrogen. APSIM is under continuous development and freely available for research purposes. Although widely used in agricultural crop modeling, APSIM's application in horticulture has been limited. SPASMO is another deterministic farm system model that has been utilised in horticultural areas of New Zealand. While several other international deterministic models exist, few or no expert users are present in New Zealand.

In New Zealand horticulture, research has primarily focused on water quantity and quality, using tools such as Overseer, SPASMO, and APSIM to address irrigation, nutrient losses, greenhouse gas emissions (particularly nitrous oxide, N_2O), and environmental impacts of management strategies. While there is some emphasis on nutrient management in vegetables, less attention has been given to soil physical and biological quality. Studies have explored the benefits of introducing diversity into crop systems and evaluated factors associated with greenhouse gas emissions such as lime purity, N_2O emissions factors for fertilizers, and the development of low-emission tractor systems. Funding from Sustainable Land Management and Climate Change (SLMACC) has supported projects related to climate change adaptations, pest and disease management, erosion control, and biosecurity. Sustainable weed, pest, and disease management practices, including reduced agrichemical use and biotechnology adoption, have been encouraged in the horticulture sector. Projects have also combined Mātauranga Māori (Māori knowledge) and western science to enhance productivity, and other areas of focus include waste management, greenhouse industries, plasticulture, recycling, and regenerative agriculture practices, considering multiple aspects such as soil health, water quality, greenhouse gas emissions, production, profitability, and human wellbeing.

Water availability and management are becoming increasingly critical due to escalating demands on this valuable resource. Assessing the impact of water shortage on crops involves three parts: quantifying crop stress resulting from water shortage, quantifying the impact of stress on crop yield and product quality, and determining spatial, temporal, and contextual variation in stress impacts. Quantifying stress involves calculating the ratio between water supply and demand, which can be carried out using the Penman Monteith equation. Water supply depends on root length density and the extent of root penetration and is best calculated using a coded model. Crop systems models use similar approaches to calculate water supplies and demands, and the appropriate model to use should be based on the crops and response variables being considered. Empirical and process models can be used to quantify the effect of water stress on crop yield and quality. Empirical models provide simple estimations, while process models like SPASMO and APSIM offer more precise predictions based on different soils and climates. The variability of stress effects across different locations and years must also be taken into account, and deterministic systems models can help in designing policies and determining individual grower responses.

For further information please contact:

Wei Hu
Plant & Food Research Lincoln
Private Bag 4704
Christchurch Mail Centre
Christchurch 8140
NEW ZEALAND

Tel: +64 3 977 7340
DDI: +64 3 325 9683

Email: Wei.Hu@plantandfood.co.nz

1 Introduction

The purpose of the Productive and Sustainable Land Use (PSLU) Farm Monitoring & Benchmarking programme is to provide the Ministry for Primary Industries (MPI) with access to data, information, and insights to (i) better understand farm/orchard/vineyard systems and performance, and (ii) provide informed analysis and advice to understand the impacts of potential environmental and other policies.

MPI is seeking information and insights from scientific and technical experts, informed by past and current research, as to: (i) what environmental metrics and key performance indicators (KPIs) are relevant for horticulture land uses and growing systems, (ii) appropriate tools and models for analysis, and, therefore, (iii) what data may be appropriate to collect and analyse from New Zealand horticulture farms and orchards. This research and technical review/assessment will help inform the approach the MPI Farm Monitoring Team may adopt in working with horticulture product groups and other stakeholders in the New Zealand horticulture sector, to collect, collate and analyse information on the environmental performance of horticulture farms, orchard, and vineyards.

The objective of the work is to obtain a research report describing:

1. The environmental metrics, relevant data, and development of risk matrices and KPIs to help assess the environmental performance of horticulture farms, orchards, and vineyards.
2. Relevant tools and models for horticulture environmental data and scenario analyses.

The scope of horticulture land use includes the production of fruit, nuts, vegetables, and wine grapes. The scope of growing systems includes outdoor production of relevant crops (annual and perennial crops) and production indoors, whether under permanent cover (i.e. glasshouses or tunnels with all year-round cover), or temporary covers (i.e. covered for part of the growing cycle only).

2 Environmental performance assessment

In this section, environmental areas of interest and environmental performance assessment in the horticultural sectors are reviewed. For this purpose, a comprehensive methodology was used to search relevant literature internationally and within New Zealand. First, searching terms (“Horticulture” or “fruit” or “vegetable” or “nut” or “vineyard” or “winegrape” or “apple” or “pear” or “berry” or “berries” or “avocado” or “kiwifruit”) AND (“water quality” or “biodiversity” or “soil heath” or “soil quality” or “water quantity” or “water use” or “climate change” or “greenhouse gas” or “carbon footprint” or “pest” or “disease” or “weed” or “biosecurity” or “fungicide” or “biopesticide” or “herbicide” or “insecticide” or “microbicide” or “mahinga kai” or “sediment” or “heavy metal” or “nitrogen” or “nitrate”) were used to search abstract or title in the Web of Science database. Second, to our best knowledge, the relevant scientific reports in New Zealand not covered in the results of previous searching were added to the literature database. Third, the whole research team had a one-day workshop to discuss any research that may have been missed from scientific papers and reports. From the literature review and workshop, it is concluded that the environmental areas of interest mainly include water quantity, water quality, soil health and soil quality, biodiversity, greenhouse gas emissions, weed, pest and disease management, heavy metals in soils, mahinga kai, and others associated with waste management, greenhouse industries, burning, natural fertilisers, and plasticulture. For each environmental topic, the environmental metrics and associated attributes needed to characterise the metrics are presented in Section 2.1.

Environmental performance and environmental impacts are often used interchangeably in discussing sustainability and environmental management. While both concepts relate to how human activities affect the environment, there are some key differences between these two. Environmental performance refers to how well an organisation or individual is managing its environmental impact to ensure sustainable use of natural resources, while environmental impact refers to the actual effects that a particular activity or process has on the environment. Environmental performance is evaluated over a period of time, while environmental effects are evaluated in relation to a specific activity or project. Environmental performance is based on established principles, frameworks, and guidelines, and is important for achieving environmental sustainability goals both nationally and internationally. For instance, the United Nations Global Compact is a framework that provides guidance to businesses on how to integrate sustainable practices into their operations. In New Zealand, environmental performance is guided by the Resource Management Act 1991 (RMA), which provides a legal framework for the sustainable management of natural and physical resources. The RMA requires that all activities that have an impact on the environment are managed in a way that ensures their environmental effects are avoided, remedied, or mitigated. This includes activities such as farming, orcharding, and vineyard management. For farms, orchards, and vineyards, environmental performance can be defined in various ways depending on the specific environmental aspects that are being considered. In general, environmental performance for these land-based activities is assessed based on their impact on the soil, water quality, biodiversity, and greenhouse gas emissions.

While metrics for environmental performance can be characterised by various methods, such as direct measurements, or modelling with different complexities, there is also interest in the development of a simple risk matrix based on easily available data such as soil, climate, and agricultural management practices data. Using nitrogen loss to waterways as an example, the development of a risk matrix for environmental performance will be discussed in Section 2.2.

Environmental metrics are usually used to assess a specific aspect of the environmental performance, such as water use or greenhouse gas emissions. However, trade-offs usually exist between various environmental performances, use of a single environmental metric may not reflect the overall environmental performance of a farm. Therefore, KPIs are generally used to measure overall performance across a range of areas, including environmental performance, particularly from the aspect of sustainability, which is the focus of Section 2.3. As KPIs are more generic to various land uses, search terms such as “sustainability”, “eco-efficiency”, “footprint”, “ecosystem services”, “life cycle assessment”, “water use”, “nutrient use”, and “energy use” were used to search abstracts in the Web of Science database.

Finally, key points and insight information are summarised in Section 2.4.

As the scope of this report is partly aligned with Hu et al. (2022), which focuses on the environmental impacts of apple production, the reference of Hu et al. (2022) is extensively cited in Section 2 of this report without explicitly referring to it to avoid repetition.

2.1 Environmental metrics to characterise various environment of interest

2.1.1 Water quantity

Metrics for water use and loss

The issue of water availability and management is becoming increasingly critical due to growing demands on this resource, mounting pressure to preserve water for environmental purposes, declining rainfall across New Zealand, especially in horticultural regions (MPI 2021), and rising temperatures leading to increased evapotranspiration. Effective management of irrigation is crucial for several reasons, especially given the expected rise in demand due to global warming and decreasing water availability as a result of declining rainfall (MPI 2021). Given that irrigation of horticultural crops often uses modern drip systems under computer control, managing and recording water use is somewhat easily managed. Indeed, irrigation consents now require water use to be recorded under an amendment to the Resource Management Act 1991.

Table 1 lists metrics and attributes for the measurement and determination of water quantity at a farm/orchard/vineyard level in New Zealand. Water quantity is usually characterised by water use, water loss, and their derivatives such as water use efficiency, water productivity, irrigation water productivity, and resiliency of horticultural land use to water.

Table 1. Metrics and attributes for the measurement and determination of **water quantity** at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
Water use	Irrigation water use per annum and its spatial and temporal distribution	For each season: Rate of application per day (mm/day), for how many days (days), area applied (ha), and percentage of area wetted (depending on irrigation method)	Growers, regional councils, irrigation schemes	Available from growers who have water meters or are part of an irrigation scheme that has monitoring and reporting of water use Percentage of area wetted is estimated to be percentage (%) of all growers who irrigate	Water use may not be useful for characterising environmental performance without considering the water scarcity, water use alone does not encompass all aspects of poor irrigation practices, such as inadequate irrigation scheduling and inefficient irrigation systems	
	Plant water use (evapotranspiration)	Time series of soil evaporation and plant transpiration	Measurements using sap flow sensors	Difficult	Can be used to reflect the real water consumption, but is costly to measure	Can be measured using sap flow sensors on few trees and multiplied for the entire stand
	Rainfall	Rainfall amount, rainfall intensity, and rainfall periods	Weather stations, NIWA, other weather information providers	Easily available	Needed for calculating water use using water balance	
	Soil water profile	Soil water content dynamics or soil water storage change at start and end of growing seasons	*In situ* measurement using soil water content sensors, or assuming no changes in soil water storage during the growing seasons	Soil water content sensors at different depths in the root zone need to be installed for soil water content measurements, or soil water content measured by taking disturbed samples and measuring it gravimetrically	Soil water content alone does not provide full information on the use of water or losses between these points, unless other data (e.g. water inputs) are available; Can be used to guide irrigation.	May not be needed at relatively large time scale (e.g. a crop season, annual) if the focus is the total amount of water usage rather than the dynamics in water use
	Frost protection	Rate of application per day (mm/day), for how many days (days), area applied (ha), over which period (months)	Growers, Regional Councils, Irrigation schemes	Data should be available from growers	For complete understanding of water use	Mainly for fruits
	Water for agrichemical spray	Spray amount (i.e. volume), spray concentration, number of spray events	Growers	Data should be available from growers	(See above)	Trivial amount which may be ignored, but worth considering it during the period of low water availability

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
	Irrigation type and scheduling practices	Irrigation type such as conventional full irrigation (e.g. based on potential *ET*), deficit irrigation, partial root zone irrigation, subsurface drip irrigation, surface drip irrigation, variable rate irrigation; Irrigation distribution, depth, frequency limitations, management and maintenance frequency, design factors, and audit system	Growers	Data should be available from growers	Can be used to understand the potential difference in water use efficiency if production data are available for the area irrigated	
	Tools/systems to assess daily water requirements	Soil water content, crop demand, application software (e.g. how much and when to put etc) /triggering decision.	Growers	Data should be available from growers who have application software installed	(See above)	
	Water supply reliability	Water demand, water supply amount	Growers, researchers, and regional councils	Data should be available from growers, researchers, and regional councils	Can be used to characterise the degree of availability of water supply on demand as a measure of water scarcity; has not been tested for its suitability	
Water loss	Drainage	Soil water content profile, crop uptake, rainfall amount, and irrigation amount	Direct measurement (e.g. drainage fluxmeter) from researchers, water balance	Difficult to measure, need professional expertise, otherwise estimate based on drainage coefficient and water input	Can be used to indicate the potential contaminant leaching, enables groundwater recharge; imprecise and overestimated drainage measurements can be obtained from fluxmeters and lysimeters, respectively	Drainage coefficient under different circumstances (e.g. soil, crop, topography, and climate) yet to be synthesised or modelled
	Runoff loss	Soil moisture profile, crop uptake, rainfall amount and intensity, surface cover, irrigation amount and intensity, slope, runoff	Direct measurement with runoff plot, numeric simulation	Difficult to measure and simulate, need professional expertise, otherwise estimate based on runoff	Can be used to indicate the potential contaminant losses via runoff, sedimentation of receiving water bodies	Runoff coefficient under different circumstances (e.g. soil, crop, topography and climate) yet to be

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
		mechanisms (infiltration or saturation excess)		coefficient and water input		synthesised or modelled
	Measures to reduce water loss or water demand	Irrigation method, ground cover (e.g. mulching), if other technologies (e.g. weather forecast) are used for irrigation scheduling	Growers	Easily available from growers	Can be used to check if water use efficiency can be improved	
Water use efficiency, water productivity, irrigation water productivity	Water use amount (including both rainfall and irrigation water use), irrigation amount, crop biomass, economic output	Irrigation, rainfall, drainage, crop yield for different parts of a product, price of crop products etc	(See above)	Data should be available from growers	Good indicators to relate water use to crop production (quantity and/or quality) and economic outputs; Scarcity is not considered (potentially can incorporate water supply reliability mentioned above)	More discussion can be found in section 2.3.1
Resiliency of horticultural land use to water	Yield stability, water use efficiency, soil health, biodiversity, irrigation efficiency and economic viability (there are also metrics)	(All attributes required to characterise these metrics listed in the left column, please refer to those in this section)	(See above)	(See above)	Reflects real-word conditions, considers multiple factors, encourages sustainable practices and help to address water scarcity; however it's difficult to quantify, may not account for external factors, limited applicability, and can be subjective	Please see sections 2.1.3, 2.1.4, and 2.3.1 for water use efficiency, soil health, biodiversity, irrigation efficiency

Different approaches have been used to characterise water use. There are two common approaches used in agriculture and horticulture areas. One approach is to measure the total amount of irrigation water. To assess this, data such as rate of application per day, number of irrigation days, and area applied, needs to be collected from growers, regional councils, or irrigation schemes. Another approach is to measure the actual water use of plants (e.g. evapotranspiration), which can be either measured directly or calculated from water balance (irrigation, rainfall, soil moisture, and drainage). To estimate the actual water use, in addition to irrigation water amount, other attributes such as rainfall amount, soil moisture, and water loss (via drainage and surface runoff) are also required. The availability of associated data is as follows:

- Rainfall data can be easily measured by nearby weather stations which are available from regional monitoring stations and the National Institute of Water and Atmospheric Research (NIWA).
- To measure soil water content at various depths within the root zone, different techniques such as time-domain reflectrometry (TDR) and neutron probe can be used. Alternatively, if the total water usage throughout the growing season is the focus, soil water content can be measured by collecting soil samples using a soil auger at the start and end of growing season. In this case, it may also be reasonable to ignore the possible changes in soil water content within the root zone without measurements. However, in cases where water usage during different stages of growth is of interest, frequent measurements of soil water content are necessary.
- Drainage and surface runoff can be directly measured using lysimeters (e.g. drainage flux meters) and runoff plots, respectively, or indirectly calculated from water balance. But their measurements tend to be costly and need professional expertise. One possible method to estimate drainage and surface runoff is by using the water input data, which includes irrigation and rainfall, and assuming a drainage or runoff coefficient. This coefficient represents the proportion of the total water inputs that will be drained or result in runoff. However, the coefficient may vary depending on multiple factors such as soil type, crop coverage, topography, and climate. Previous measurements under similar conditions can provide an estimate of the coefficient. For example, the surface runoff coefficient tends to decrease as crop coverage, slope, soil compaction, and rainfall intensity increase (Mu et al. 2015). Conversely, coarser soils with less vegetative growth in flatter areas tend to have higher drainage coefficients. Current work being carried out in conjunction with Zespri Group Limited in kiwifruit orchards and with the Foundation for Arable Research (FAR) for arable lands is focussing on directly measuring runoff losses of water and nutrients and establishing the drainage coefficients with new technologies. These projects are at early stages of development.
- Although not used directly for plant growth, water used for other purposes (e.g. frost protection, agrichemical spray) may also need to be considered from an environmental perspective. But compared with irrigation water, less water is typically needed. In addition, frost protection is likely to coincide with times of low water demand for plant growth, so water use for frost protection is less likely to be an issue. Though water use for agrichemical sprays is much less than that required for frost protection, if this happens during the period of low water availability, the small amount of water used for agrichemical sprays can further increase the pressure on water use. In addition, it is more important to ensure there is access to frost protection although there might be other non-water based frost protection methods available to growers.

It is questionable whether water use can be used to reflect environmental performance because the degree of water scarcity at a given site is not considered. For the same reason, even for the same site, total water use per annum cannot fully capture the environmental performance due to seasonal variations in water allocation and use. For this reason, identifying seasonal distributions of irrigation and rainfall can be useful when assessing environmental performance. Based on water availability and water demand, water supply reliability can potentially be used to measure the degree of water scarcity in different growing stages (seasons). In addition, water use efficiency and environmental performance can vary depending on factors such as the irrigation method used, whether irrigation was applied at the appropriate time based on crop needs (e.g. with the use of reliable application software), and other management practices (e.g. ground cover), even when the same amount of water is applied. Resiliency of horticultural land use to water is used to characterises the ability of the land and the crops grown on it to withstand and adapt to water-related stress factors, such as drought, flooding, and changes in precipitation patterns. A resilient horticultural system is one that can maintain or recover its productivity and ecosystem functions despite these stressors. Metrics that can be used to define the resiliency include yield stability, water use efficiency, soil health, biodiversity, irrigation efficiency, and economic viability.

Irrigation and other management practices that affect water use

In New Zealand, 77% of water allocation is used for irrigation (Clothier et al. 2012). Various irrigation systems (e.g. drip, surface irrigation, subsurface drip irrigation, micro-sprays, micro-sprinklers) and irrigation management (e.g. deficit irrigation, partial root zone irrigation, variable rate irrigation, and conventional full irrigation) have been compared globally for different horticultural crops (e.g. fruits, outdoor vegetables, greenhouse vegetable, and grapevines) in terms of crop yield (Abdalhi & Jia 2018; Cheng et al. 2021; Wang et al. 2022; Yadav et al. 2022), water use (Abdalhi & Jia 2018), harvest index, water productivity (Chand et al. 2021; Wang et al. 2022; Yadav et al. 2022), irrigation water productivity (Wang et al. 2022), food quality (Adu et al. 2019; Chand et al. 2021; Sonawane & Shrivastava 2022), economic parameters (Yadav et al. 2022), root growth (Sonawane & Shrivastava 2022), and quality of surface and ground water (O'Shaughnessy et al. 2019; Yasuor et al. 2020). For example, compared with surface irrigation methods, drip irrigation was found to be the most robust, profitable and cost-effective method of irrigation (Yadav et al. 2022). Compared with surface drip irrigation, subsurface drip irrigation significantly increased yield, water productivity, and irrigation water productivity by 5.4%, 4.0%, and 6.8%, respectively, with effects varying with management practices, climate, and soil (Wang et al. 2022). A partial root zone drying method was found to be a better alternative compared with conventional irrigation methods. This method saved 50% more water without a reduction in yield and with improved yield quality for different crops such as tomatoes in Italy, beans in Austria, and navel oranges in Australia (Sonawane & Shrivastava 2022). Zhou et al. (2020) advocated the need to transit irrigation strategies from conventional field irrigation method, which relies on water balance and yield models, to a new approach which incorporates information on crop water demand and considers the relationship between water, yield, and quality at a growing season scale in a comprehensive manner.

Other management practices that improve water use efficiency (WUE), crop performance, and soil health have been studied. Zhang & Wang (2018) reviewed plastic mulch (polyethylene (PE), polypropylene (PP), and soil bio-degradable plastic mulch (BDM)) used in perennial fruit cropping systems and found that the choice of plastic mulch (PE, PP, and BDM) system will influence plant growth and productivity, the soil environment, and management of pests and diseases. BDMs are presently not widely used in perennial fruit crop production but could be a more sustainable option relative to traditional plastic mulches. However, there are emerging concerns about the environmental effects from the breakdown of agricultural plastics in soils. While the abundance of micro- and nano-plastics is more extensively studied in water, new research is being conducted on the abundance and effects on biota and physical properties (Allouzi et al. 2021). In an extensive review of soil management practices that can improve WUE, Hatfield et al. (2001) noted that modifications to the soil surface (e.g. tillage and cover crops) can improve water infiltration and therefore increase water availability within the root zone. However, the authors noted that excessive tillage can also have detrimental effects on soil quality, such as soil structural degradation and compaction, and potentially reduce the hydraulic conductivity of the soil. Crop cover and residue management may also improve water availability and retention. Surface residues and cover crops were found to reduce surface evaporation, by reducing soil temperature, impeding vapour diffusion, absorbing moisture into mulch tissue, and also reducing the wind speed gradient (Hatfield et al. 2001). Similarly, O'geen (2006) suggested that increasing soil organic matter, for example through the use of compost and mulch, could help increase infiltration rates of apple orchard soils. Although cover crops offer many benefits, they can also compete with primary crops for water. For example, in arid and semi-arid regions such as the Chinese Loess Plateau, intercropping of soybean and peanut with apple crops was found to inhibit the fine roots of apple trees in the top 60 cm of soil depth. However, this competition led to the promotion of root growth in the 60–100 cm soil depth as an adaptation to water scarcity (Sun et al. 2018).

Horticultural water use in New Zealand

In many cropping systems of New Zealand, water is often the limiting factor for successful crop production and plays an essential role in many soil functions and services (Clark et al. 1999; Périé 2015; Fahad et al. 2017). For example, measured data from 'Golden Delicious' apples grown in the Moutere hills of Nelson, New Zealand, on Mapua light grey sandy loam, showed that irrigating trees when the soil water content was at 80% and 20% availability (with sufficient water applied at each irrigation to return soil to field capacity) resulted in cumulative yield increases of 16% and 9%, respectively, over 5 years. However, significant yield increases were only observed in 2 of the 5 years when compared to non-irrigated trees due to water deficit caused by insufficient rainfall (Hewett 1976). For many crops, the amount of water required is determined by a number of intrinsic factors, such as crop type, age, local climate, and soil type (Adeniran et al. 2010). Water use efficiency (WUE) is the ratio of the amount of crop biomass per volume of water consumed (Zhuo & Hoekstra 2017) and provides an indication of how efficient water use has been by a particular crop. Green & Clothier (1999) found that measured daily water use of mature 'Splendour' apple trees (~14 years old), grown on a Manawatu fine sandy loam in the Manawatū region of New Zealand, by TDR and heat-pulse, had a maximum value of more than 40 L d^{-1} per tree during the summer, while during cooler autumn months this was greatly reduced to 20 L d^{-1} per tree; 70% of the water uptake (i.e. 24 L) occurred in the top 40 cm of the soil profile. Similarly, modelling of water uptake of the same trees, Green et al. (2003b) estimated maximum water use in the region of 70 L d^{-1} per tree during summer and 20 L d^{-1} in autumn. Clothier et al. (2012), looking at the potential water footprint of exported New Zealand apples and estimated the water use of exported apples to be 130 L kg^{-1} of apples. While soil water loss can occur due to evaporation at the soil surface, evapotranspiration and runoff (Gregory et al. 2000), Green et al. (1989) also found that 6% of the daily transpiration rates of 'Red Delicious' apples, in Hawke's Bay, New Zealand, was accruing overnight. This amounted to 5 L d^{-1} per tree of the total daily evapotranspiration rate of the apple trees.

In general, water use by horticultural crops is lower than that of pasture, due to the different canopy architectures, which determines the crop factor (see below). However, inappropriate water application (time of day and duration) can severely effect crop productivity and survival (MPI 2021). The FAO-56 procedure for estimating crop water use relies on the so-called crop factor, *K*c, to link plant-water use to the reference evapotranspiration, *ET*o (Allen et al. 1998). The reference *ET*o is the evapotranspiration from well-watered, full-cover short crops, namely pasture. The *K*c values obtained from the FAO-56 procedure change during the season as canopy coverage changes. Estimating the canopy is perhaps the biggest challenge without well parametrised models. The canopy change affects dynamics between canopy, understory, and bare areas, and, hence, water use. Modelling of crop phenology and leaf-area growth is accounted for in models such as SPASMO. This modelling relies on a dual crop factor approach to account for the changing leaf area of the crop (Green et al. 2008).

When it comes to horticultural crops, peak water demand usually occurs during mid-summer, with lower requirements in spring as the canopies develop and in autumn when leaves eventually senesce. Perennial horticultural crops have crop factors that generally range between 0.3 to 0.6 due to canopy architecture and seasonal growth patterns (Green et al. 2003a; Green et al. 2008). The low crop factor of 0.3 was related to areas like the Gimblett Gravels in Hawke's Bay where there is limited vegetative vigour. Nut crops tend to have larger and denser canopies for mature trees, and mid-season *K*c values that are usually close to or greater than 1. This means that nut crops may use slightly more water than established grass crops (Allen et al. 1998).

Also, seasonal water demand for horticultural crops tends to be lower than for pastures due to their seasonal phenology, shorter growing season, and ability to extract water deeper through their deeper root systems. In comparison to pastures, outdoor, annual vegetable crops will use less water (Martin et al. 1992; Jamieson et al. 1995; Martin & Jamieson 1996; Reid & Gillespie 2017; Michel et al. 2019). This is because their average canopy coverage over a growing season is lower due to the seasonal pattern of leaf growth, resulting in longer periods of bare or partially covered soil. Because of differences in phenology and length of growing seasons between crops and crop cultivars, water use will vary widely. There have been a number of studies of drought and water use responses for annual crops conducted in Canterbury using the purpose built rainshelter facility at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln. Crops studied under the rainshelter include potatoes, field peas, carrots, ryegrass seed, clover seed, wheat, and maize (Martin et al. 1992; Jamieson et al. 1995; Martin & Jamieson 1996; Reid & Gillespie 2017; Michel et al. 2019). Unlike tree and vine crops, many vegetable crops have shallow root systems that limit their ability to extract water from deeper soil profiles.

Plant water use in greenhouses or enclosed in shade cloth structures can be less than outdoors due to lower radiation interception and to a lesser extent reduced wind speeds (Möller & Assouline 2007; Fernández et al. 2010). Inside a plastic greenhouse with a perennial grass in Almería, south-eastern Spain, reference *ETo* ranged from values slightly less than 1 mm d^{-1} during winter to values of approximately 4 mm d^{-1} during summer in July, which was about 20% lower inside a plastic covered greenhouse than grass growing outdoors (Fernández et al. 2010). Moreover, higher yields are often achieved for indoor growing compared with outdoors, increasing plant water use efficiency. However, lack of *Kc* factors for some horticultural crops for New Zealand conditions, particularly their spatial (e.g. regional) and temporal (e.g. seasonal) dynamics is a knowledge gap. For example, we may not be able to use the same *Kc* across Northland, Bay of Plenty, Hawke's Bay, Marlborough, and Otago for a given crop over its growing life. The value and seasonal pattern of *Kc* is very dependent upon canopy architecture, which is a result of the pattern of vegetative vigour, canopy structure, and management practices. There are good *Kc* values for apples, grapes, and kiwifruit, and these accounted for the seasonal dynamics (Green & Clothier 1995).

Water use is also affected by the relationship between crop and understory and how these are managed. Models such as SPASMO account for the complex pattern of water uptake from the row, and the inter-row, as well as the zone wetted by drippers, and that only receiving rainfall (Green et al. 2008). Not only is water use by perennial horticultural crops lower than full cover, shallow-rooted crops, but the need for irrigation is generally lower. Firstly, the roots of perennial tree and vine crops penetrate deeper than pasture, enabling great access to the soil's reserves of water (Green & Clothier 1995). Furthermore, perennial horticulturalists aim to limit irrigation, especially during fruit maturation, as excess water only encourages vegetative vigour which limits fruit quality (Mills et al. 1996). In the context of new storage development, horticultural land-uses such as kiwifruit, avocado, vineyards, pip and stone fruit, citrus, and vegetable production, are the land-use options that provide the highest financial value from newly irrigated areas (Dark et al. 2021). Because climate change causes a decrease in rainfall across New Zealand (MPI 2021), it is crucial to ensure that water is used efficiently by applying appropriate methods, amounts, and timing to achieve high-quality fruit yields with minimal water usage. Fortunately, all irrigation consents are now required to be monitored under the Resource Management Act 1991, and modern computer-controlled systems enable easy recording. This monitoring also allows for the reporting of the water footprint of production, which may be required for eco-credentialling purposes.

2.1.2 Water quality

In horticulture, environmental performance studies related to water quality has been mainly focusing on nutrients (e.g. primarily nitrogen and phosphorus), sediment, and pesticide losses via leaching and runoff (Pant et al. 2004; Cherry et al. 2008; Carstensen et al. 2020; Gentile et al. 2022; Hardie et al. 2022; van de Vlasakker et al. 2022). The leaching processes that connect land management practices to the water quality of underlying aquifers are described in Clothier & Green (2021). Leaching is the product of drainage and the concentration of solutes in the draining water. The processes that control drainage are dominated by rainfall, and to a lesser extent irrigation. Drainage is an important process by which underlying aquifers are recharged. The concentration of solutes is controlled by natural processes of mineralisation in the rootzone, but dominated by agrichemical management by growers. Müller et al. (2014) and Clothier & Green (2021) described recent advances in modelling pesticide transport in soil and pesticide risk-reduction knowledge. In a review of Integrated Pest Management (IPM), Walker et al. (2017) noted that "… organophosphate insecticide use was eliminated by 2001, replacing it with pest monitoring systems, threshold-based selective insecticides, and biological control. More recently, new demands for ultralow-residue fruit have increased the adoption of mating disruption and use of biological insecticides. Widespread adoption of selective pest management has substantially reduced the status of previously important pests, including leafrollers, mealybugs, leafhoppers, and mites for improved phytosanitary performance, and contributed to major reductions in total insecticide use." There is a move, plus legal market-access requirement towards the use of more-benign pesticides (Walker et al. 2017). As well, more comprehensive monitoring is indicating the impacts that agriculture, in general, and horticulture, in particular, are having on water quality. Export requirements have created a long history of record keeping of pesticide use in horticulture, and spray diaries are an integral part of reporting, especially in perennial horticulture. The trends in usage are reported frequently (Manktelow et al. 2005) "… to provide up-to-date data on pesticide use in New Zealand and related land use trends over time. Such data are needed to help identify pesticide use issues, to determine appropriate research and management policies, and to help maintain consumer and market confidence."

Table 2 lists metrics and attributes for the measurement and determination of water quality at a farm/orchard/vineyard level in New Zealand. Usually, concentration of contaminants (e.g. nitrate, phosphorus, sediment, and pesticide) and water flow amount (e.g. drainage and runoff) need to be obtained to calculate the contaminant discharge.

Table 2. Metrics and attributes for the measurement and determination of **water quality** at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons
Nitrate leaching (other contaminants)	Nitrate concentration in leachate	Porous suction cup, lysimeters or drainage flux meters for collecting leachate for direct measurements of nitrate concentration or nitrogen balance modelling (nitrogen fertiliser data, initial nitrogen profile, climate, soil, crop growth) for indirect calculation	Direct measurements need researchers' assistance; Data for modelling can be obtained from growers, Regional Councils, NIWA, PFR, SMap (Manaaki Whenua Landcare)	For modelling, irrigation and fertiliser data are easily available from growers, climate easily available from NIWA, soil properties can be available from S-map, crop growth can be obtained from PFR, but resolution may not be high enough, so soil and crop data may need to be measured	Relevant to surface water and groundwater quality. All these methods have their pros and cons and are best suited to research. Suction cups. A large number of samplers are normally required to represent field variability. Solute in the matrix should be at equilibrium with drained solute. Accurate soil water balances are required to estimate drainage. Absence of continuous measurements could result in missing drainage events Lysimeters and drainage flux meters also normally require suction (wicks or plates) to accurately simulate in situ processes in the surrounding soil. Repacking of soil changes physical and biochemical conditions that can reduce accuracy. Nitrogen samples need to be treated and analysed soon after drainage events to avoid risk of further nitrogen transformations.
	Drainage	Drainage fluxmeter or in situ lysimeter (direct measurement), water balance modelling (irrigation, climate, soil, crop growth, management practices)	(See above)	(See above)	
	Land area	Area of a certain horticultural land use	Growers and Regional Councils	Easily available from growers or regional councils	
Nitrogen runoff in overland flow	Nitrate and NH_4^+ concentration in surface overland runoff	Difficult to measure at sub-catchment scale, modelling is needed, parameter inputs are dependent on the model used	Can be measured at point and runoff plot scales and scaling up using models	A new prototype runoff measurement system for overland flows has been developed by PFR	Nitrogen samples need to be treated and analysed soon after events to avoid further nitrogen transformations; Relevant to surface water quality. As yet, there has been little analysis of the early data.
	Surface overland runoff	(See above)	(See above)		
Phosphorus runoff loss	Phosphorus concentration in surface overland runoff	Dissolved and sediment-bound phosphorus, difficult to measure, modelling is needed, parameter inputs are dependent on the model used	(See above)	(See above)	Can be used to indicate the potential of eutrophication in waterways; Relevant to surface water and groundwater quality
	Surface overland runoff	(See above)	(See above)	(See above)	

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons
Sediment loss	Sediment concentration in runoff	Difficult to measure, modelling is needed, parameter inputs are dependent on the model used	(See above)	(See above)	Relevant to surface water quality
	Surface overland runoff	(See above)	(See above)		
Pesticide loss (fungicide, insecticide, herbicide, agrichemical including *Escherichia coli*)	Pesticide concentration in surface overland runoff	(See above)	Can be measured at point and runoff plot scales and scaling up using models.	Not yet implemented	Relevant to surface water and groundwater quality
	Surface overland runoff	(See above)	(See above)		
Untreated discharge from indoor growing systems	Nitrogen, phosphorus, pesticide concentrations, and discharge volume.	Water quality samples of stored solution and discharged volume. Information about the discharge site: soil, land use and weather conditions Additional information may be required depending on RMA consents or Council Plans.	Growers' records required for Code of Practice for the Management of Greenhouse Nutrient Discharges. Council resource consent records (RMA legislation).	Data held by growers. Data may also be held by councils if required through RMA process.	Quality of the data and recording may vary.

NIWA: National Institute for Water and Atmospheric Research, New Zealand; PFR: The New Zealand Institute for Plant and Food Research Limited.

Nitrate leaching is a major concern for New Zealand's horticulture industry, as it can have significant environmental impacts. Nitrate is a compound that is essential for plant growth, but when it is in excess in the soil, it can leach or runoff and contaminate groundwater or surface water. Nitrate concentration in drainage is usually measured by taking samples using lysimeters (including drainage flux meters), porous suction cups or calculated using nitrogen balance modelling. The drainage can be measured by drainage fluxmeter or lysimeter, but soil water balance modelling is commonly used to calculate the drainage. Excessive nitrate is a threat to aquatic ecosystems and human health, so it is a key metrics for water quality. Excessive nitrate in waterways can cause eutrophication and harm aquatic life, with adverse impacts starting at concentrations of around 1–5 mg/L and becoming more severe at concentrations above 10 mg/L. Ingesting high concentrations of nitrate has been linked to methemoglobinemia “blue baby syndrome”, which occurs mainly in infants. This condition reduces the ability of blood to carry oxygen. New Zealand has set a maximum contaminant level (MCL) for nitrate in drinking water of 50 mg/L (11.3 mg nitrate-N/L), which is consistent with the World Health Organisation’s guideline for nitrate in drinking water. However, nitrate leaching is hard and expensive to measure, and it relies heavily on modelling which has high uncertainty. This is due to the intricate nature of the hydrological and biochemical processes involved, as well as the numerous parameters required for accurate modelling. In addition, nitrate concentration can be very spatially and temporally variable, which is hard and expensive to measure (Lilburne et al. 2012). In this regard, Thompson (2021) proved that successful real time ‘in situ’ nitrate measuring was possible using a nitrate sensor in a Hawke’s Bay onion field. The Quick N test is a simple, rapid field test that is used to estimate the nitrogen content of a plant or soil sample. It is commonly used during the growing season and has been found to have a close correlation with laboratory-measured nitrate concentration (Foundation for Arable Research 2019). It is being used by arable and vegetable growers in New Zealand to manage their fertiliser requirements. However, the recommendations generated by the Quick N Test were found to underestimate the amount of fertiliser nitrogen needed to achieve the yield potential of both irrigated and dryland wheat crops (Beare et al. 2022c). This may indicate that Quick N test may not be a good approach for measuring the potential of nitrate leaching, because the amount of nitrate leaching depends on the balance between nitrogen supply (e.g. fertiliser, initial mineral nitrogen, and nitrogen mineralisation) and crop need.

While most studies on water quality focus on outdoor crops, nutrient discharge from indoor cropping systems can also lead to water contamination when not appropriately managed. In Western Europe, regulations on discharges from soil-less cropping systems are being imposed to achieve zero emissions of nutrients from greenhouses by 2027, with other rules to limit losses from soil bound systems (van der Salm et al. 2020). In general, throughout Western Europe, the collection and reuse of drainage water from soil-less indoor growing systems is obligatory. Nutrient losses from soil-bound systems is managed through a combination of tools and measurements to help growers tune their nutrient applications to crop demand and limit discharge volumes and nutrient concentrations from soil bound systems (van der Salm et al. 2020).

In New Zealand, discharges of surplus nutrients from indoor cropping systems are managed through plans under the Resource Management Act 1991 and resource consents. *Growers’ Guide to The Management of Greenhouse Nutrient Discharges* (Lewthwaite et al. 2007b) and *A Code of Practice for the Management of Greenhouse Nutrient Discharges* (Lewthwaite et al. 2007a) have been developed by industry and MPI. On this basis, it appears that the New Zealand approach is less onerous than proposed in the Netherlands for growing indoor crops in soil-less media. The Code of Practice provides for discharging nutrients on to land, where and at times that they can be taken up by pasture or crops but requires provision of storage to retain the nutrients until they can be applied at times they can be removed by plants.

Nutrient leaching losses

Nitrogen losses to water are a global problem in intensive horticulture production systems, such as vegetable cropping. In New Zealand, high nitrogen leaching rates have been found in vegetable production. For example, the Arawhata Stream in the Horowhenua District has one of the highest nitrate concentrations in New Zealand as a result of vegetable cropping in this region (Bloomer et al. 2019).

Several field studies conducted on range of vegetable crops, including spinach, cabbage, cauliflower and potatoes, in the Pukekohe area (Martin et al. 2001; Francis et al. 2003; Williams et al. 2003). The research, mostly conducted through the Franklin Sustainability project was designed to improve fertiliser management. Large leaching losses ranged from 60 to nearly 300 kg N/ha for a spinach crop. The largest losses in these studies 20 years ago reflect practices that would no longer be considered good practice. Nitrate leaching losses from irrigated potatoes grown over summer in Canterbury were 46 kg N/ha when water and fertiliser nitrogen were managed well but increased to 109 kg N/ha when both were poorly managed (Francis et al. 2006). Based on this research, improvements in nitrogen management and timing, rates and number of fertiliser applications and crop management, e.g. use of cover crops and improved cropping rotations to mop up surplus soil mineral nitrogen, is expected to considerably reduce the nitrate leaching risk. However, growing shallow rooted, high value vegetable crops over winter where relatively large amounts of residue area left in the paddock postharvest in areas of high rainfall will still have high risk of leaching and run-off.

Minimising nitrogen surpluses in cropping soils is a major challenge for growers. Decomposition rates of residues and mineralisation of soil organic matter are difficult to predict and is a large knowledge gaps where more research is urgently needed. In both vegetable and perennial fruit crops the amount of nitrogen returned through residues can be greater than the fertiliser inputs (Thomas et al 2020). The processes are affected by amount and residue composition, the influence of tillage and incorporation of residues, and these are regulated by soil biophysical and climatic factors. It is important to better understand soil mineralisation and residue decomposition process as these can supply equivalent or greater amounts of nitrogen to crops than applied fertiliser (Francis et al. 1992; Francis et al. 1994; Francis et al. 1998). Good management practice such as minimising periods of fallow and having actively growing crops or catch crops is one of the key mitigation factors (Francis et al. 1998). Conversely, both poor irrigation and fertiliser management have been demonstrated to greatly increase leaching losses in a cropping rotation study in Canterbury (Francis et al. 2006; Thomas et al. 2012). A range of mitigation options for reducing nitrate leaching have been reviewed in an earlier report for MPI (Thomas et al. 2021). They concluded that the best options were around active management of soil and plant nutrients, e.g. nutrient budgeting, soil tests, crop rotations and catch crops, to minimise an excess of nutrients in the soil that increases the risk of leaching losses.

Measured and simulated nitrogen leaching losses under fruit crops (e.g. kiwifruit, apples) in New Zealand are relatively low (e.g. 1 to 33 kg nitrogen (N) ha^{-1} y^{-1}) (Green et al. 2010; Journeaux et al. 2019). There have been only a few published field measurements of nitrogen leaching in horticultural production (Goh & Haynes 1983; Clothier et al. 2012; Norris et al. 2016). For example, Norris et al. (2016) reported results from their study termed ‘rootzone reality’ using a network of drainage fluxmeters to measure nutrients losses under a range of cropping systems in the Canterbury, Manawatu, Hawke’s Bay, Waikato, and Auckland regions, including both irrigated and non-irrigated sites. This did not include perennial horticulture, but rather was focused on arable and vegetable systems. They found across the network of drainage fluxmeters, measured losses have ranged from 0.2 to 226 kg N/ha and from 0.01 to 0.56 kg P/ha. Nitrate-N was the dominant form of nitrogen loss while most phosphorus was lost as dissolved reactive phosphate. Drainage occurred predominantly

(78–100%) over the mid-autumn to early spring period (April to September). The variability in nitrogen and phosphorus losses among different sites reflect the duration of the monitoring period as well as the wide range of climate, management (e.g. irrigation, crop type etc), and soil characteristics.

The majority of the nitrogen leaching estimates from vegetable and perennial fruit crops are derived from various research and nutrient management models. There is still more development to do in relation to modelling some of the complex crop management practices. For example, the commonly used Overseer model needs to be upgraded to improve the modelling of nutrient flows and management.

The occurrence of nutrient leaching is determined by drainage from rainfall and irrigation events (Neilsen et al. 2008), that are seasonally focused in temperate climates (Riga & Charpentier 1999). For example, in New Zealand kiwifruit orchards, nutrient leaching occurs mostly during winter when soil moisture is close to field capacity, rainfall is high, and vines are not actively growing and extracting nutrients (Green pers. comm. 2023). The quantity of nutrients leached is influenced by nutrient inputs (Neilsen et al. 2008) and management strategies such as orchard design, planting density, and sward management. Management strategies to decrease nutrient leaching losses include decreasing the amount of nutrients applied, optimising the timing of applications, and applying woody mulches (Merwin et al. 1996; Neilsen et al. 2008).

As noted above, vegetative vigour is unwelcome for perennial fruit crops. Fruit growers tend to be cautious users of fertilisers, especially nitrogen, as excessive nitrogen can stimulate vegetative growth. For instance, in *Actinidia chinensis* var. *deliciosa* 'Hayward' kiwifruit orchards, growers typically apply 75–100 kg N ha^{-1} y^{-1} to achieve a yield of 40 t ha^{-1}. However, nitrogen inputs across kiwifruit orchards in New Zealand vary from 0 to 226 kg N ha^{-1} y^{-1} (Carey et al. 2009; Morton 2013; Gentile et al. 2022). Similarly, in New Zealand apples, average nitrogen applications range from 30 to 80 kg N ha^{-1} y^{-1} to achieve a yield of 70 t ha^{-1} (Goh & Haynes 1983; Morton 2013; Gentile et al. 2022). The recommended nitrogen application rates per ha per year for other crops are 95 kg N for avocados, 50–72 kg N for blueberries, 35 kg N for cherries, 150 kg N for onions, 200–360 kg N for potatoes, 5–68 kg N for wine grapes, and no nitrogen fertiliser for chestnuts, honey & manuka, peas and truffles (Thomas et al. 2020). The parsimonious use of nitrogen by horticulturalists is also responsible for the low nitrate leaching in most horticultural land use. For example, Hardie et al. (2022) found nitrate leaching under apples to be11.4 kg NO_3-N ha^{-1} y^{-1}, based on measurements and modelling.

Not only is it important to monitor fertiliser applications in horticulture, but also it is necessary to record the amount and quality of organic amendments, including pruning, to account for the nutrient mineralisation from these sources. In New Zealand scenarios, based on Overseer modelling, Journeaux et al. (2019) found minimal change in nitrogen leaching losses by eliminating nitrogen fertiliser use, and greater nitrogen leaching losses when compost or clover understory crops were used in place of nitrogen fertiliser inputs owing to lower crop nutrient extraction and higher nitrogen mineralisation. They suggest that reducing fertiliser inputs offers little impact on nutrient losses relative to an already well-managed fertiliser regime in perennial horticulture crops such as pipfruit, summerfruit, kiwifruit, avocado, and viticulture.

Soil biochar addition was found to significantly decrease short-term nitrate leaching from the surface layer of a sub-alkaline soil under temperate climatic conditions (Ventura et al. 2013), but it was found to have no significant effects on either the concentration or the flux of nitrate leached from the A1 horizon in a Young Apple Orchard of Tasmania (Hardie et al. 2015). Nitrate leaching losses are largely driven by drainage, and a recent study showed that soil compaction can potentially decrease soil evaporation and hence increase risk of drainage and leaching losses in flat areas (Yi et al. 2022). In Italy, it was suggested that the minimisation of nitrogen leaching in orchards must be based on reducing the presence of NO_3^- ions at the end of the vegetative period (late autumn) since the major risk of water contamination with leaching occurs during winter and in early spring (Tagliavini et al. 1996).

Nutrient (nitrogen and phosphorus) runoff losses

Nutrient losses from runoff are assumed to be minimal in New Zealand perennial horticulture production systems because of the typically flat terrain in orchards and grassed alleyways, which reduce erosion risk. However, this may change if horticulture expands to more sloping land. There are few studies reporting runoff nutrients losses from horticulture in New Zealand. Wheel traffic from vegetables at Pukekohe was found to significantly affect runoff and soil erosion, and they concluded that cultivating wheel tracks is a simple and effective practice to increase infiltration of rainfall and reduce erosion rates on clay-rich, strongly structured soils (Basher & Ross 2001).

Modelled phosphorus losses for perennial horticulture in the Hawke’s Bay region ranged from 0.13 to 0.58 kg phosphorus (P) ha^{-1} y^{-1}, with 55–78% of this loss occurring via leaching and drainage instead of via runoff. Modelled runoff phosphorus losses in the Gisborne region ranged from 0.1 to 1.0 kg P ha^{-1} y^{-1} for kiwifruit, grape, and citrus production (Gentile et al. 2014a). Similarly, Clothier & Green (2017) modelled the annual New Zealand national average for vineyard phosphorus losses from combined leaching and runoff to be 0.25 kg P ha^{-1} y^{-1}. New data on runoff losses from orchards and arable farms through new measurement technologies should soon become available from projects underway.

Sediment and pesticide losses

In New Zealand, studies relevant to sediment losses mainly focus on the vegetable sector, while relatively few studies have been carried out in other horticultural land uses. Sediment yield from the 1.8 km^2 Whangapouri basin near Pukekohe, used predominantly for market gardening, suggested that large amounts of soils were mobilised within paddocks by storms in the Pukekohe area, but little of this sediment was transported as suspended load in streams (Basher et al. 1997). A four step procedure has been proposed to minimise soil erosion and sediment loss for vegetable production (Barber 2014). The four steps include (1) paddock assessment, (2) implement control measures for stopping or controlling water entering the paddock, (3) implement erosion control measures to keep soil on the paddock, and (4) implement sediment control measures to manage the water and suspended soils that move off the paddock. Increasing buffer strip widths and set-aside are suggested to manage sediment and phosphate loss to drains and waterways (Bloomer et al. 2019). Winter-spring period was identified to be important for sediment generation, so attempts to reduce sediment loss should target this period of the year (Basher et al. 1997).

In New Zealand, 41% of all pesticides were used for horticulture between 1999 and 2003 (Manktelow et al. 2005). However, according to national surveys, concentrations of most pesticides in groundwater were usually low (Cameron et al. 2002), and their occurrence had been attributed to non-point sources of contamination (Sarmah et al. 2004). Müller et al. (2010) introduced a concept of the pesticide footprint for estimating the total loss of pesticides to soil, water (both surface and ground water), and air, and their respective impacts on humans and ecosystems, per product unit in a life-cycle framework.

Many factors affect leaching and groundwater contamination potential of pesticides in New Zealand. These include the number and amounts of pesticides applied, pesticide properties (e.g. chemical structure, water solubility, vapour pressure, sorption coefficient, and persistence), soil properties (e.g. organic matter content, microbial activities, soil texture, pH, microporosity, and water content), environment (e.g. temperature, rainfall and recharge rate, and sunlight), and management practices (e.g. irrigation, previous exposure of soil to pesticides, cultivation, land application of organic manure, and mode of application) (Cameron et al. 2002). Untreated discharge from indoor growing systems is likely to contain a range of pesticides. Purification treatment of the discharge, great utilisation of the water via recirculation, and zero discharge systems are approaches to minimise pesticide discharge. In the Netherlands, there is a target to purify >95% of the contaminants in drainage water along with recirculation of the drainage water and (nearly) zero liquid discharge (van der Salm et al. 2020). In addition, education of pesticide users on the proper handling and application methods, management decisions assisted by modelling are also important for minimising the risks of pesticide contaminations (Cameron et al. 2002).

2.1.3 Soil health and soil quality

Soil Health definition and its importance

Soil health has been defined by the United States Department of Agriculture, Natural Resources Conservation Service(USDA-NRCS) as “the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans” (Karlen et al. 2019). It is adapted from the earlier definition of soil quality by Doran & Parkin (1994), defined as “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health”. While the terms soil health and soil quality are usually used interchangeably and therefore can be considered equivalent (Bunemann et al. 2018), efforts are also made to distinguish them (Maikhuri & Rao 2012). According to Hill Laboratories in New Zealand, soil quality focuses more on inherent soil characteristics, while soil health focuses more on the dynamic nature of soil. Healthy soil is characterised as good soil tilth, sufficient depth, sufficient supply (but not excess) of nutrients, optimal pH, low population of pathogens and insect pests, high and diverse population of beneficial organisms (including earthworms), low weed pressure, free of harmful chemicals and toxins, and resistant to degradation (Soil Quality vs Soil Health | Hill Laboratories – NZ (hill-laboratories.com)). An integrated framework for soil health was developed by Maanaki Whenua – Landcare Research by connecting various knowledge forms (including Māori knowledge and perspectives) with soil science (Stronge et al. 2023). In this framework, “well-being” concepts are being explored from a soil health perspective.

A key component of soil health is the importance of soil functions and ecosystem services (e.g. supporting high yield and crop quality, storing carbon, and reducing greenhouse gas (GHG) emissions). The capacity of a soil to perform soil functions and ecosystem services can be assessed by a suite of chemical, physical, and biological indicators (Lazcano et al. 2020). It is proposed that soil health is dependent on the maintenance of four major functions: carbon transformations, nutrient cycles, soil structure maintenance, and the regulation of pests and diseases (Kibblewhite et al. 2008). The Importance of soil health for ecosystem services (Griffiths et al. 2018; Rinot et al. 2019), sustainable management (Doran 2002; Lal 2015; Griffiths et al. 2018), and human wellbeing has been highlighted. The objective of regenerative agriculture that most aligns with various definitions of sustainable agriculture is environmental improvement. This emphasises the crucial role of maintaining or enhancing soil health to regenerate and support multiple ecosystem services (Schreefel et al. 2020).

Indicators for soil health and soil quality

Different soil properties are usually measured in different studies. Figure 1 shows the frequency of different soil health properties used all over the world (Raghavendra et al. 2020), with the five most frequently measured soil properties being soil organic carbon (SOC)/ total organic carbon (TOC), pH, available phosphorus, water storage properties (e.g. water holding capacity and available water capacity), and bulk density. While soil health indicators are generic for different land uses, whether soil is healthy, or not, is dependent on crop type, soil functions and ecosystem services of interest. For example, Lazcano et al. (2020) highlighted that soil micro-organisms' roles in wine production go beyond supporting the typical functions of a healthy soil and are important in regulating the organoleptic properties of wine. This concurs with findings that vineyard fungi accounted for 40% of the source of this diversity in harvested juice and ferments (Morrison-Whittle & Goddard 2018), implying the importance of soil microbes for flavour, aroma, and quality of wines. Soil iron, aluminium, carbon/nitrogen ratio, ciliates, flagellate protozoa communities, total bacteria, negative bacteria, and soil worm count were found to be important predictors of avocado yield (West et al. 2021). While greater soil fertility generally results in higher vegetative vigor and greater production in pastoral and arable systems, the same may not hold true for perennial horticulture. In this context, improving soil fertility by enhancing organic matter content can lead to counterproductive vegetative growth that negatively impacts fruit yield and quality (Clothier et al. 2021).

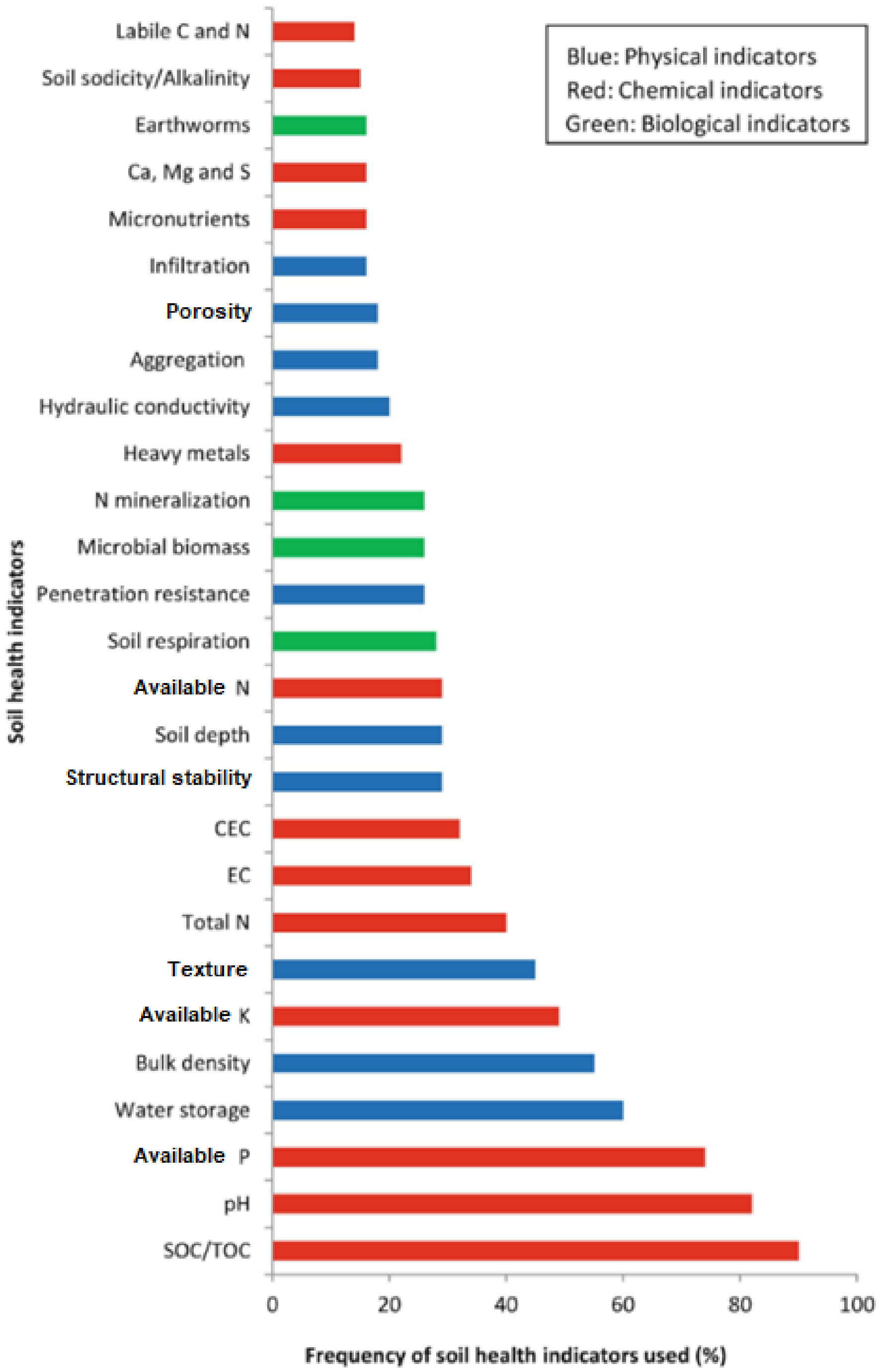

Figure 1. Frequency of different properties of soil health used all over the world (Raghavendra et al. 2020). (C: carbon; N: nitrogen; Ca: calcium; Mg: magnesium; S: sulphur; CEC: cation exchange capacity; EC: electric conductivity; K: potassium; P: phosphorous; SOC: soil organic carbon; TOC: total organic carbon).

Soil health is of great interest to various agricultural land use in New Zealand and worldwide (Sparling et al. 2004; Haney et al. 2018; Tahat et al. 2020). In New Zealand, many regional authorities monitor soil quality of various land uses for State-of-the-Environment (SOE) reporting. The soil quality indicators usually include total carbon, total nitrogen, mineralisable nitrogen, pH, Olsen P, bulk density, and macroporosity. Decrease in macroporosity from soil compaction can be a potential issue in New Zealand horticulture (Hu et al. 2021). In the Marlborough region, for example, average soil macroporosity of 0–10 cm was below the critical value of 10%. According to the SOE national survey during 2014–2018, 29% of sites in horticulture (cropping) and 45% of all land uses in New Zealand were below the target range for macroporosity (Stats NZ 2023). Soil compaction affects a range of environmental issues, such as soil-borne disease (Winkelmann et al. 2019), greenhouse gas emissions, leaching losses, runoff, and sediment losses (New Zealand Apples & Pears 2017; Hardie et al. 2018; Hu et al. 2021). For Olsen P, 61% of sites in cropping (market gardens, and grain and seed growing) and 46% of sampled sites in orchard/vineyard were above the target range sampled between 2014 and 2018, implying a high risk of water pollution (e.g. eutrophication). According to the New Zealand national survey conducted 1995–2001, Olsen P was much greater under pastures and cropping (44–49 mg cm^{-3}) than under plantation and indigenous forest (10 mg cm^{-3}) (Sparling & Schipper 2004). This reflected the regular application of superphosphate to stimulate the growth of grass and arable crops in New Zealand. However, as only 15–30% of phosphorus fertiliser is taken up by crops (Cordell et al. 2009), high concentrations of Olsen P in the soil indicate that too much phosphorus has been applied (MfE & Stats NZ 2021).

In addition to the seven common soil quality indicators, other soil properties were also measured in some regions, such as aggregate stability, trace elements, saturated hydraulic conductivity, soil respiration, and base saturation (Sparling et al. 2004; Drewry et al. 2021). Drewry et al. (2021) found that copper concentrations were elevated over time in horticultural and market gardens sites in the Wellington region. Hermans et al. (2020) measured soil bacterial community composition using 16S rRNA gene sequencing. They found that soil bacterial community composition can correctly determine land use type with 85% accuracy, differentiate sites grouped by key physico-chemical properties with up to 83% accuracy, and assign correct soil quality scores with 50–95% accuracy. Although national and regional survey data do not necessarily relate to soil health or soil quality at the farm scale, soil properties are measured at the farm level in horticulture to understand their relationship with crop performance or environmental outcomes (Benge et al. 2007; Morton et al. 2008; Sparling et al. 2008; Deurer et al. 2009; Deurer et al. 2012). However, these studies typically did not explicitly link soil properties to soil health assessment.

Approaches to assess soil health and soil quality

There are no standardised methods to assess soil health (Lazcano et al. 2020). Table 3 lists some soil health assessment methods/framework in New Zealand and overseas. In New Zealand, visual soil assessment (VSA) guidelines were developed based on photographs and scorecards for specific landscapes such as “flat to rolling” or “hill country” mainly for cropping and pastoral grazing (Shepherd 2000). The inherent site properties (land use, soil type, texture, moisture condition, and seasonal weather conditions) were also used to refine local data interpretations (Karlen et al. 2019). While this is a quick, simple, soil type-independent method to relate plant performance to soil condition and management practice, it is mainly related to plant performance rather than all key soil functions and ecosystem services.

Table 3. Metrics and attributes for assessing soil health/soil quality in New Zealand and overseas.

Metrics	Attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes	References
Visual Soil Assessment	Visual scoring of key bio-physical indicators of soil quality (soil structure, earthworms, soil smell, and potential rooting depth)	N/A	Not available, needs to be measured	Quick and simple to relate plant performance to soil condition and management practice, being independent of soil type; An objective method, training is required, and mainly related to plant performance	New Zealand focused, mainly for cropping, pastoral grazing on flat to rolling country, has been applied in 15 countries	Visual Soil Assessment, bioagrinomics, (Shepherd 2000)
A minimum soil test dataset	Total carbon, total nitrogen, mineralisable nitrogen, pH, Olsen P, bulk density and macroporosity	Landcare Research	May be available from Landcare Research upon request	Seven properties explained majority of variations in lager data (12–17 properties); Direct measurement of the 7 properties is needed for a target farm	New Zealand soil quality national monitoring programme, seven properties explained 88% of the variance in the dataset with 511 sites from various land uses	(Sparling & Schipper 2002; Sparling & Schipper 2004; Sparling et al. 2004)
Soil bacterial community composition	16S rRNA gene sequencing test	N/A	N/A	It's related well with other physico-chemical properties; But not widely used, lack of assessment of its capability to represent soil functions, and expensive to measure	Soil bacterial community composition can assign correct soil quality scores with 50–95% accuracy	(Hermans et al. 2020)
Soil health score (SHS)	1-day CO_2-C analysis, WEOC, WEON (SHS=1day CO_2-C/10*WEOC/100*WEON/10)	N/A	N/A	An integrative soil testing approach, offers insight into complex interactions between soil chemistry and biology; Mainly relate to nutrient cycling	This tool analyses soil nutrient dynamics recognising soil is a living, highly-integrated, and evolved system	(Haney et al. 2018)
Soil quality index	Multiple physical, chemical and biological properties	N/A	N/A	Based on multiple soil ecosystem services; Expensive to measure, good understanding of relationships between soil properties and functions are required	Three steps including indicator selection, indicator interpretation and integration are included in this tool	(Andrews et al. 2004; Andrea et al. 2018)
Soil health index	Multiple physical, chemical and biological properties, ecosystem services quantified	N/A	N/A	Based on multiple soil ecosystem services; Expensive to quantify	Ecosystem services are highlighted for assessing soil health	(Rinot et al. 2019)

WEOC: water extractable organic carbon; WEON: water extractable organic nitrogen.

As discussed above, a minimum dataset (i.e. total carbon, total nitrogen, mineralisable nitrogen, pH, Olsen P, bulk density, and macroporosity) protocol has been proposed to monitor soil quality of various land uses including horticulture and cropping in New Zealand (Sparling & Schipper 2002; Sparling & Schipper 2004; Sparling et al. 2004). Macroporosity and bulk density are used to assess soil physical health especially linked to soil compaction; pH is used to measure soil acidity which determines nutrient availability; Olsen P is used to measure soil fertility; total carbon is used to reflect food and energy amount available to microorganisms; total nitrogen is to measure the total amount of nitrogen in soils. Previous studies have found that the seven properties of the minimum dataset explained the majority (88%) of variations in large datasets of 12–17 soil properties from 511 sites. A web-based tool, SINDI (soil indicators), was designed to help to interpret the quality or health of a soil (Landcare Research 2023). However, no single indicator has been developed by Maanaki Whenua Landcare Research or other organisations for a comprehensive assessment of soil health for comparison purpose.

Hermans et al. (2020) found that soil bacterial community composition determined by 16S rRNA gene sequencing could differentiate sites grouped by key physico-chemical properties with up to 83% accuracy and assign correct soil quality scores with 50–95% accuracy. This method potentially indicates the suitability of one single test for soil health assessment. However, this method has not been widely used to confirm its capability to relate to soil functions and ecosystem services, and it is relatively expensive. Sainju et al. (2021) also discovered that carbon dioxide (CO_2) flushes during a 1-day incubation following the rewetting of dried soils, measured with an infrared gas analyser, had a stronger correlation with soil properties and crop yields. As such, this method is recommended as a straightforward, speedy, dependable, and cost-effective means of assessing soil health in dryland cropping systems.

Soil health can be evaluated in terms of nutrient cycling using a soil health score that incorporates CO_2, water extractable organic carbon and nitrogen (Haney et al. 2018). To measure the potential of soil to supply nitrogen and estimate the amounts of micro-organisms present, anaerobically mineralisable nitrogen is used. A rapid hot water extractable carbon (HWEC) test has been suggested as an alternative to other tests, as it is highly correlated with soil microbial carbon and soil aggregate stability (Ghani et al. 2003).

In New Zealand, the hot water extractable organic nitrogen (HWEON) has become a standard test to assess soil nitrogen availability and nitrogen supply potential in commercial laboratories (Curtin et al. 2006; Curtin et al. 2017). The HWEON test has been tested with field trials at multiple locations and crops (Beare et al. 2022a; Beare et al. 2022b), and predictions of in-field nitrogen mineralisation from the HWEON test are closely related (R^2 = 0.96) to the measured nitrogen mineralisation based on soil moisture and temperature data (Beare et al. 2022b). This indicates that the HWEON test, coupled with information on soil temperature and moisture content, can be used to predict the supply of nitrogen from mineralisation over a growing season (Beare et al. 2022a; Beare et al. 2022b).

Increasing fertiliser nitrogen rates does not result in significant differences in the crop yields (Beare et al. 2022b). Thus, application of nitrogen fertiliser by considering crop needs and nitrogen supply (i.e. initial mineral nitrogen, nitrogen mineralisation, and its temporal changes) can maintain optimal crop growth and minimise environmental impacts (Beare et al. 2022b; Beare et al. 2022c). It has been observed that nitrogen supplied by the initial mineral nitrogen plus the mineralisable nitrogen is sufficient to meet the crop demand of a carrot crop, whereas for kale and beetroot crops, the yield per unit of nitrogen supplied declines substantially at medium and high fertiliser nitrogen rates. It has been reported that 75 kg N ha^{-1} can support asparagus growth for 3 years without detectable changes in fern nitrogen concentration. The fertiliser should be applied close to fern growth to minimise leaching risk, especially on shallow or low water holding soil types (Bloomer 2022). However, nitrogen fertiliser application recommendations generated by the Quick Test Mass Balance Tool have been found to underestimate the amount of fertiliser nitrogen needed to achieve the yield potential of both irrigated and dryland wheat crops (Beare et al. 2022c).

Linking soil health assessment with ecosystem services delivery

While most methods for assessing soil health do not or only relate to a certain soil functions and ecosystem services, Andrews et al. (2004) developed a soil management assessment framework (SMAF) for assessing soil quality/health by integrating multiple soil health indicators from biological, physical, chemical, and nutrient categories, with each indicator representing a unique set of important soil functions (Karlen et al. 2019). In this method, a three-step process including indicator selection, interpretation, and integration is suggested (Andrews et al. 2004; Andrea et al. 2018) (Figure 2). Andrea et al. (2018) presented the usefulness of using the SMAF based on multiple soil ecosystem services to identify the best soil management practices that deliver multiple ecosystem services and to support resource-efficient production. More recently, Rinot et al. (2019) comprehensively reviewed current methodologies for assessing soil health. They argued that a holistic approach for soil health assessment is crucial to sustaining land resources and highlighted that a soil health index should reflect soil ability to provide all ecosystem services (e.g. providing, supporting, and regulating). For this reason, Rinot et al. (2019) proposed a multivariate-complex soil health approach, where soil health is assessed by monitoring of all ecosystem services provided by soils.

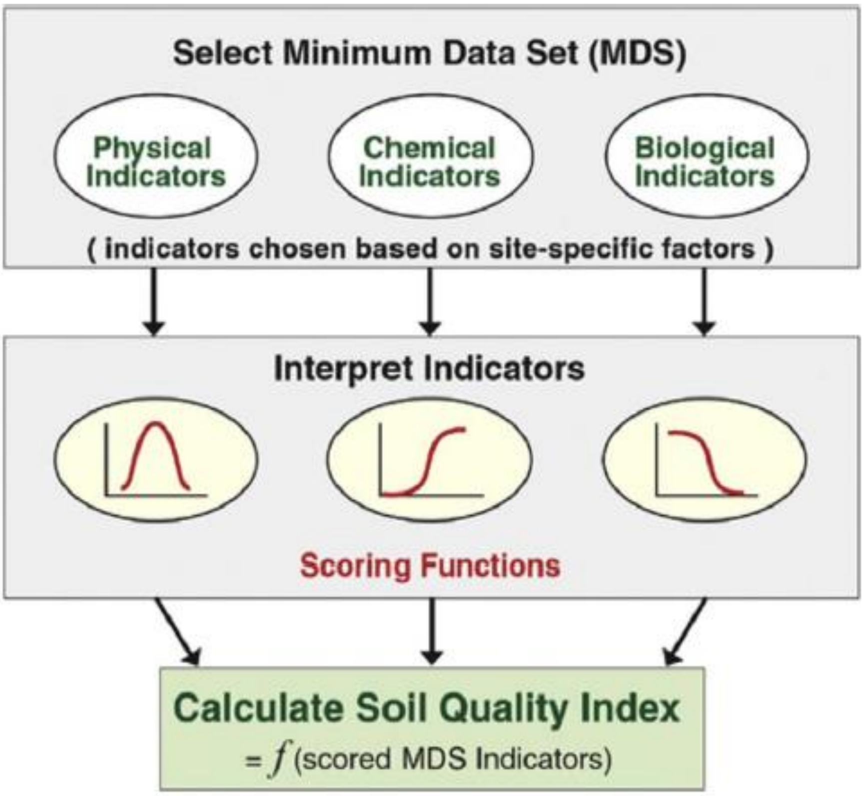

Figure 2. The three-step process of the Soil Management Assessment Framework (SMAF). In the “Interpret Indicators” step are reported the three types of scoring curve: mid-point optimum range, more-is-better and less-is-better. (source: United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS) Soil quality website http://soilquality.org/tools/smaf_intro.html) [Accessed 2022 August 22] (Andrea et al. 2018).

Different horticultural land uses provide different ecosystem services/disservices. There is a general agreement that soil plays a central role in providing ecosystem services. Therefore, future soil health assessment in New Zealand should be made by linking key soil properties to the full ecosystem services. Studies have shown the benefits to develop crop-specific guidelines or reference values that would help growers manage soil health for an optimum expression of the terroir (Lazcano et al. 2020), which is a knowledge gap yet to be filled.

A clear definition for regenerative agriculture is lacking. Globally, however, soil health and biodiversity has been the focus for many reviewed definitions (Schreefel et al. 2020). Regenerative agriculture in New Zealand aims to improve soil health, increase biodiversity, and reduce environmental impact while producing high-quality food and fibre. It involves a holistic approach that integrates traditional knowledge and modern science to create a sustainable and regenerative farming system. Although soil health has been extensively explored, our understanding of what constitutes healthy soil is limited, particularly without considering the desired ecosystem services. Thus, when evaluating soil health in the context of regenerative agriculture, it should also be assessed in terms of environmental impact and food production.

2.1.4 Biodiversity

Importance of biodiversity in ecosystem services

Biological diversity, often referred to as biodiversity, plays a critical role in food security, nutrition, and the supply of vital ecosystem services (Naeem et al. 2009; FAO 2019a). It also promotes resilience of production systems and livelihoods, provides options for the sustainable intensification of production, and supports livelihoods (FAO 2019a). It is widely recognised that people's wellbeing depends on the health of the natural environment around them (Department of Conservation 2022). Changes in land and sea use, direct exploitation, climate change, pollution, and introduced invasive species are the main drivers of indigenous biodiversity losses (Department of Conservation 2022), which is particularly culturally important in New Zealand (Meurk & Swaffield 2000). Regulatory changes are underway in New Zealand to address the loss of indigenous biodiversity and improve conservation efforts. The New Zealand Biodiversity Strategy 2020–30 aims to protect and restore ecosystems, increase predator control, and support Māori involvement in conservation efforts. The Resource Management Amendment Act 2020 requires councils to protect significant natural areas from development and manage indigenous vegetation and habitats. Proposed amendments to the Wildlife Act 1953 strengthen protections for threatened species, increase penalties for illegal hunting and trading of wildlife, and recognise the importance of Māori cultural values in wildlife management. These changes reflect the growing recognition of the importance of indigenous biodiversity in New Zealand.

Biodiversity types and assessment

Table 4 lists metrics and attributes for the measurement and determination of biodiversity at the farm/orchard/vineyard level. Biodiversity can be classified as aboveground and belowground biodiversity. They can be further classified as plant biodiversity (Nicholls & Altieri 2013), vertebrate biodiversity, invertebrate biodiversity (e.g. nematode biodiversity, Potter & McKeown (2003)), and microbial biodiversity (e.g. bacteria, fungal, and archaea biodiversity) (Ritz & Griffiths 2001; Frac et al. 2018; Turley et al. 2020). Among which, soil microbial biodiversity (Jeffries et al. 2003) and nematode biodiversity (Sofo et al. 2020) are also used as soil health indicators. In addition, measurements of biodiversity of aquatic ecosystems (e.g. wetlands, streams, ponds etc) in farms can be very important. This is because aquatic biodiversity is associated with health of the whole ecosystem, economic benefits, regulatory compliance (e.g. over application of nitrogen can cause eutrophication hence negatively affects aquatic biodiversity), and sustainable agriculture.

Table 4. Metrics and attributes for the measurement and determination of **biodiversity** at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources data	Ease of sourcing data	Pros and cons	Notes
Aboveground biodiversity	Plant biodiversity	Number of species in an area, number of individuals per species (e.g. productive plant, non-productive plants)	Direct measurement needed	Not available, needs to be measured	Relatively easy to measure, based on quadrat sampling may not be useful to indicate soil functions in horticulture as some species are controlled by management practices (e.g. weed control)	Measurement frequency varies depending on the purpose. E.g. regular intervals (e.g. every year or every few years) are needed to track changes in biodiversity over time; Ad hoc surveys are often used to assess the impact of a specific event or disturbance; Continuous monitoring can provide valuable insights into how biodiversity responds to changes in the environment
	Vertebrate biodiversity	Number of species in an area, number of individuals per species (mainly birds in New Zealand)	(See above)	(See above)	Can be a good indicator of habitat (e.g. soil, water, air etc); Too dynamic, but not difficult to measure	(See above)
	Invertebrate biodiversity	Number of natural enemies, pollinators, species in an area, number of individuals per species	(See above)	(See above)	Total number of natural enemies can be quantified; the impact of both natural enemies and pollinators on crop health/yield, respectively, can be determined reasonably easily and is currently being carried out at The New Zealand Institute for Plant and Food Research Limited (PFR); There are invertebrates other than natural enemies and pollinators that can be monitored (e.g. decomposers, worms, pests, rare species) that would give different measures of ecosystem health	(See above), birds can also be natural enemies of pest insects/weeds; Diversity of invertebrates is often used as a measure in itself and is easier than monitoring both natural enemies (since these first need to be identified as feeding on the pest/weed) or pollinators (since these need to be shown to not only visit the flower but to transfer pollen)
	Microbial biodiversity	Number of species in an area, number of individuals per species (e.g. bacteria, fungi, archaea)	(See above)	(See above)	Easy to sample, but expensive and difficult to measure species, easier to measure functions	(See above)
Belowground biodiversity	Invertebrate biodiversity	Number of species in an area, number of individuals per species (e.g. nematodes, annelids, arthropods)	(See above)	(See above)	Relatively easy to measure from soil cores collected, may reflect soil health condition; but not clear which species are linked to which soil functions	(See above)

Metrics	Primary attributes	Secondary attributes	Likely sources data	Ease of sourcing data	Pros and cons	Notes
	Microbial biodiversity	Number of species in an area, number of individuals per species (e.g. bacteria, fungi, archaea)	(See above)	(See above)	Easy to sample, and may reflect soil health condition; But expensive and difficult to measure species, easier to measure functions	(See above)
Aquatic biodiversity	Species diversity	Number of species in a waterbody (wetland, stream, pond etc), number of individuals per species	(See above)	(See above)	Comprehensive measure, and easy to understand; but difficult to measure and limited scope	(See above)
	Invasive species	Number of species in a waterbody (wetland, stream, pond etc), number of individuals per species	(See above)	(See above)	Easy to identify and can indicate ecosystem health; can be difficult to manage, limited scope	(See above)

There are a number of biodiversity indices, and all are standardised (Katayama et al. 2019). The most common ones are Simpson's index, Shannon-Weiner Index, Richness, and the Evenness Index. Different indices are used to answer different questions. Alpha, beta and gamma diversity give an indication of biodiversity at different scales (alpha at a site, beta for between sites within the landscape and gamma at the landscape scale). However, these are not the measures that would be used to monitor ecosystem services, which are based on identification of the species involved in the service and their ecological function(s). Although various indices have been proposed to characterise biodiversity, most of them are based on the numbers of species in an area and number of individuals per species. Different species are usually included in different land uses. Even for the same land use, the species of interest are also variable. For example, in terms of taxonomical representation of insects and animals in vineyards, globally, arthropods were found to be the most represented taxonomic group, followed by birds and mammals (Paiola et al. 2020). Therefore, when it comes to managing land use and conserving biodiversity, it's important to account for the specific species that are present in each area and their particular needs and requirements. This requires careful study and monitoring of local ecosystems, as well as ongoing efforts to protect and restore habitats for key species.

The scope and focus of ecological studies can vary depending on the research question and the goals of the study. Some studies may focus on a single species or a group of related species, while others may look at multiple taxonomic groups or even entire ecosystems. For example, researchers may conduct studies on a specific species if it is of particular conservation concern, such as a threatened or endangered species, or if it plays a critical ecological role in the ecosystem. These studies may aim to understand the species' habitat requirements, behaviour, or interactions with other species, and may inform management and conservation efforts. On the other hand, studies that look at multiple species or taxonomic groups can provide a more comprehensive understanding of the ecological processes and interactions within an ecosystem. These studies may examine the food web, species interactions, and the impacts of environmental factors on biodiversity, among other topics. The need to consider interactions between different taxonomic groups is highlighted by Paiola et al. (2020). For example, beneficial microbial organisms can be transferred to the grape by wasps, which contributes to delivering ecosystem services (Stefanini et al. 2012). In New Zealand, Coelho & Michelsen (2014) proposed a methodology for assessing the impact of land use on biodiversity using ecological structures as opposed to information on number of species. The ecological structure approach focuses on the organisation of biological communities and ecosystems, including the patterns of species composition, distribution, abundance, and diversity. It includes both the physical and biological components of an ecosystem, as well as the interactions among those components.

Evaluation of biodiversity indicators

Ideally, a biodiversity indicator should have a linear relationship with the specific entity or aspect of biodiversity that is being assessed (Duelli & Obrist 2003). Three indices are proposed for biodiversity evaluation in agricultural landscapes. They represent the three value systems: conservation (e.g. protection and enhancement of rare and threatened species), ecology (e.g. ecological resilience, ecosystem functioning, based on species diversity), and biological control (e.g. diversity of antagonists of potential pest organisms) (Duelli & Obrist 2003). Duelli & Obrist (2003) proposed that the quality and reliability of commonly used indicators could and should be tested with a three-step method: (1) the motivations and value systems and their corresponding biodiversity aspects or entities have to be defined; (2) a number of habitats have to be sampled as thoroughly as possible with regard to one or several of the three value systems or motivations; (3) test the linear correlations of a choice of easily measurable indicators with the entities quantified in the second step. A previous study was conducted to determine if there are common approaches in selecting biodiversity indicators in ecology and environmental policy, and to explore which criteria biodiversity indicators were scientifically tested against to determine their suitability (Heink & Kowarik 2010). Their results demonstrated different patterns for selecting biodiversity indicators in the different fields of application. Surprisingly, few biodiversity indicators are empirically tested to determine if they meet the criteria by which they were purportedly chosen (Heink & Kowarik 2010). To assess the suitability of a biodiversity indicator, it should be tested against all of the criteria relevant for its selection (Heink & Kowarik 2010).

Influences of glyphosate on soil biodiversity

In a greenhouse experiment conducted at the University of Natural Resources and Life Sciences in Vienna, Austria, it was discovered that the herbicide glyphosate decreased root mycorrhisation and the biomass of arbuscular mycorrhizal fungal spores, vesicles, and propagules in white clover. Mycorrhizal fungi are considered vital species because they play a key role in plant nutrient uptake and enhance plant resistance to stress. They also contribute to soil aggregation by forming symbiotic relationships with the vast majority of terrestrial plant species (Tisdall & OADES 1982; Smith & Read 2010; Begum et al. 2019).

However, there is a considerable amount of conflicting research regarding the effects of glyphosate on soil functions and microbial communities. For instance, some studies suggest that glyphosate drift doses on non-target plants may lead to increased plant growth and susceptibility to plant pathogens, but these effects have not been well-documented (Duke 2020). While the preponderance of evidence indicates that glyphosate does not harm plants by interfering with mineral nutrition and has no significant effects on soil microbiota (Duke 2020), the outcome of glyphosate-phosphorus interaction in the soil is dependent on soil properties, biotic factors, climate, and weather conditions. Furthermore, it is still unclear to what extent glyphosate-mediated changes in the plant volatilome affect pollination or pest control, and global studies suggest decreased ecosystem multifunctionality in agricultural fields managed with pesticides compared to organic farming (Ruuskanen et al. 2023). Despite growing concern about the consequences of using large quantities of glyphosate-based herbicides in agroecosystems, the potential effects on non-target soil organisms and soil functioning are mostly unknown, and few studies have been conducted in field conditions (Hagner et al. 2019). The inconsistencies in results may be due to the fact that most studies are lab-based and may not be representative of natural systems, and glyphosate formulations can obscure the actual impact of the active ingredient glyphosate.

Biodiversity studies in New Zealand horticulture

In New Zealand horticulture, the studies on biodiversity have focused mainly on perennial fruit orchards, such as kiwifruit, apples and grapes.

Most biodiversity studies in New Zealand are associated with invertebrate. For example, Richards et al. (2007) compared different types of kiwifruit orchards in New Zealand for identifying the best invertebrate indicators of soil quality. Soil nematode assemblages were found to be sensitive to management practices but impractical to use, while the bait lamina test was inexpensive but needed further development. Earthworms were recommended as suitable indicators and are recommended for the monitoring program. Organic orchards had higher earthworm populations and percentages of omnivorous nematodes, indicating differences in soil food webs. Todd et al. (2011) compared the impact of organic and integrated pest management (IPM) systems on invertebrate communities in kiwifruit orchards in New Zealand. The researchers found that significantly more taxa were collected from the organic orchards in all three trapping periods, and the invertebrate assemblages collected from the two orchard types were significantly different. The presence of more predators, parasitoids, herbivores, fungivores, and omnivores in the organic orchards suggests that these systems may have more resilient ecosystem services. Gillespie & Wratten (2012) investigated the effects of habitat fragmentation on butterfly populations in intensively managed farming landscapes in New Zealand. They studied the Greening Waipara project, which aims to enhance ecosystem services by returning native plants to viticultural landscapes, to establish whether plantings improve non-target invertebrate biodiversity. Remnant patches of native vegetation in unproductive areas were found to be crucial for sedentary species, but native planting areas were not essential for butterflies. These findings are discussed in the context of conservation in and around farmland in general. Larsen et al. (2014) conducted a study comparing different trapping methods for monitoring Hymenoptera in organic apple orchards in New Zealand. The most effective method for sampling the order Hymenoptera and two parasitoid species was found to be yellow sticky traps, while white pan traps were best for sampling native bees from the family Halictidae. The choice of preservative in the pan traps significantly affected the catch of Hymenoptera overall and Halictidae. Most Hymenoptera were more abundant within the orchards than at the shelterbelt, except for Halictidae. The results suggest that targeted trapping methods should be used for different Hymenoptera taxa. Todd et al. (2016) conducted a study to explore the relationship between ground-active invertebrates in organic and integrated pest management (IPM) kiwifruit orchards and 14 management practices. The study results indicated that in organic orchards, the diversity of natural enemies and detritivores was significantly correlated with less toxic agrichemical sprays. Moreover, higher amounts of vegetative ground cover in organic orchards were correlated with greater diversity of detritivore and herbivore taxa. The differences in magnesium application rates also explained some variation in herbivore and detritivore communities. The study suggested that altering IPM orchard management practices could increase invertebrate biodiversity and improve ecosystem services. However, careful pest control measures should be taken to ensure successful outcomes. Malone et al. (2017) compared the diversity of invertebrates in Hawke's Bay commercial apple orchards using three different pest management systems: Integrated Fruit Production, with or without codling moth mating disruption, and certified organic. They found that the invertebrate communities, but not groundcover plant communities in the alleys differed significantly between organic orchard and integrated pest management systems, and the use of codling moth disruption had no influence on the invertebrate communities. In addition, they found pest management system affected herbivores, predators, and parasitoids, but not omnivores, detritivores, and fungivores. Apple pests were also different between two orchard systems, but their natural enemies were not affected.

Vertebrate biodiversity studies in New Zealand mainly focus on birds. For example, the Agricultural Research Group On Sustainability (ARGOS) conducted a study to compare bird abundance and diversity in certified organic and conventional kiwifruit orchards in New Zealand (Rate et al. 2006). The study found that organic orchards had a significantly higher total bird count and proportion of native species than conventional orchards. Growers were aware of the birds in their orchards and recognised the potential of birds as ecological, economic, and social indicators of sustainability. The conservation of biodiversity is crucial for the long-term sustainability of the kiwifruit industry. Coleman (2010) examined the impact of Integrated Management (IM) and organic practices on the environmental health of kiwifruit orchards in New Zealand, using birds as environmental indicators. The study found that gold and organic orchards had higher species richness than IM green orchards. The study also looked at the potential use of fantails as an indicator of orchard environmental health and found that they were present in higher numbers on organic orchards with strong seasonal changes. However, further research is needed to determine whether fantails can be used as reliable indicators. The study emphasises the importance of seasonal variation when investigating the impact of land management practices on environmental health.

Microbial biodiversity and plant biodiversity were also explored in perennial crops. Wardle et al. (2001) conducted a study on a kiwifruit orchard in New Zealand over 5 years to determine the effect of ground management strategies on soil biota. Their findings showed that treatments that enhanced basal resource inputs consistently supported higher concentrations of microbial biomass and activity, which in turn resulted in higher diversity of nematodes and Collembola. Litter decomposition rates were also found to be greater in these treatments. However, the effect on higher trophic rates of the decomposer food web varied across treatments. The study emphasises the need to consider multiple trophic rates and intensification modes in long-term experiments on soil biota. The recently concluded Vineyard Ecosystems programme by the Bragato Research Institute, The New Zealand Institute for Plant and Food Research Limited (Plant & Food Research), and The University of Auckland investigated the impact of vineyard management on soil biota. The programme looked at soil biota as part of the wider grape growing ecosystem in New Zealand, to better understand the influence of season, region, and management on vineyard biodiversity. The 7-year programme, with 5 years of data collection across two regions and 24 sites, has yielded an abundance of data sets that shed a light on vineyard soils and how they interact with vines, cover crops, and climate, in a contemporary (with herbicide) and future (no herbicide and low synthetic pesticide) setting (https://bri.co.nz/2022/12/06/the-big-picture-vineyard-ecosystems/). This programme has shown that promoting biodiversity in and around vineyards can have a positive impact on grape quality and yield, as well as on the overall health of the ecosystem. This can be achieved through practices such as planting cover crops, maintaining native vegetation, and providing habitat for beneficial insects and wildlife. Shields et al. (2016) evaluated the potential benefits of low-growing, endemic plant species as Service Providing Units (SPUs) or Ecosystem Service Providers (ESPs) in vineyards. Fourteen plant species were evaluated for their ability to provide weed suppression, conservation of beneficial invertebrates, soil moisture retention, and microbial activity. The potential for ecosystem dis-services by hosting a key vine moth pest was also quantified. The study found that enhancing plant diversity in vineyards can deliver SPUs, harbour ESPs and therefore deliver ecosystem services, and that winegrowers are willing to follow these protocols.

In New Zealand, spatially explicit models of ecosystem service indicators were developed to aid in resource management using the ecosystem services approach (Ausseil et al. 2013). These models assessed the regulation of climate, soil erosion, water flow and quality, food and fibre provision, and natural habitat provision and were utilised to evaluate land-use scenarios in the Manawatu catchment. The results showed that soil erosion control, carbon sequestration, and provision of wood had the most significant relative changes in ecosystem service indicators. Coelho & Michelsen (2014) proposed a methodology for assessing the impact of land use on biodiversity using ecological structures rather than the number of species. The model was applied to kiwifruit production in New Zealand and demonstrated that productivity values depend on the area the results were normalised against. The proposed alternative vulnerability scale had little influence on the final outcome. The model enables a consistent comparison of product systems on an international basis. van den Belt & Blake (2014) conducted an analysis of the New Zealand literature on ecosystem services in agro-ecosystems using four frameworks. The literature primarily focuses on assessing benefits from changing land management practices and values to the New Zealand public. Trade-offs in land-use decisions are highlighted, but critical gaps in the literature suggest an impediment to integrating the ecosystem concept into decision-making. The study recommends expanding research to include social and cultural aspects and linking supply and demand for ecosystem services, including the effectiveness of institutions using the ecosystem services approach. MacLeod et al. (2016) explored how survey effort for environmental monitoring can be optimised by using statistical power analysis. They used pilot survey data to determine the amount of survey effort needed to detect specified trends in 13 environmental variables related to New Zealand kiwifruit orchards. The study provided a template for other industries to optimise survey design and reduce inefficiencies and opportunity costs.

New Zealand is facing a decline in biodiversity due to increasing land use pressures, and a considerable proportion of remaining indigenous biodiversity occurs on farmland in private ownership. Enhancing existing biodiversity or reintroducing structural diversity can increase biodiversity on-farm. The successful integration of biodiversity into decision-making on-farm requires explicitly accounting for biodiversity considerations in farm planning and design. Maseyk et al. (2019) proposed embedding the natural capital and ecosystem services approach into the farm planning process to quantify and value both on- and off-farm benefits associated with indigenous biodiversity. The approach recognises that indigenous biodiversity contributes to a wide range of benefits, including cultural, environmental, social, and economic values.

It has been reported that loss of indigenous cover has continued in New Zealand, with 49% of environments having lost indigenous cover from 1996/97 to 2001/02, and the highest rates occurring where indigenous cover was already most depleted (Walker et al. 2006), which severely threatened ecosystem services brought by biodiversity.

The ‘Greening Waipara’ Project began in 2005 in the Waipara Valley, North Canterbury, New Zealand (Barnes et al. 2008). In this project, functional agricultural biodiversity (FAB) was introduced to vineyards and farms in the form of native New Zealand plants, as well as introduced species such as buckwheat and phacelia, which resulted in ecosystem services being substituted for unsustainable oil-based inputs (e.g. pesticide). FAB is a concept that refers to the use of diverse agricultural ecosystems to promote sustainable and productive agriculture. FAB recognises that biodiversity is not just about the number of species present, but about the ecological functions and interactions that occur between them. In agriculture, FAB seeks to promote ecosystem services such as pollination, pest control, soil fertility, and nutrient cycling, which are critical for maintaining the productivity and sustainability of agricultural systems. In practice, FAB involves the implementation of a range of management practices designed to promote biodiversity and enhance ecosystem services in agricultural systems. This can include practices such as diversification of crop rotations, planting cover crops, integrating livestock into cropping systems, promoting agroforestry, and providing habit for beneficial insects. The Foundation for Arable Research (FAR) has undertaken significant work on biodiversity on arable farms in New Zealand, which is of relevance to the broader context of functional agricultural biodiversity. FAR’s work on biodiversity in arable farming has demonstrated the importance of promoting biodiversity in agricultural systems and the potential benefits that can be realised by adopting FAB practices. This work is relevant not only to arable farming but also to agriculture more broadly and can contribute to promoting sustainable and productive farming systems. In recent years, there has been a significant focus on promoting biodiversity in agricultural landscapes in other countries such as UK (Brooker et al. 2021; Smith et al. 2023), and numerous research studies have been conducted to understand the importance of biodiversity for sustainable agriculture and to identify practical solutions for enhancing biodiversity on farms. However, there is a lack of research and monitoring of robust indicators of terrestrial biodiversity in New Zealand production landscapes (Moller et al. 2008), although there is clear evidence that agricultural intensification has degraded aquatic biodiversity.

Pollination studies in New Zealand horticulture

Pollinators are essential for the reproduction of many plant species and the production of food. Relevant studies are associated with the decline in insect pollinators and their impact on global food security (Van der Sluijs & Vaage 2016), effects of climate change on plant-pollinator interactions

(Forrest 2015), pollinator conservation (Senapathi et al. 2015), and effect of pesticides on pollinators (Brittain et al. 2010).

Rader et al. (2012) investigated whether unmanaged pollinators could replace honey bees in providing pollination services to food crops. The authors assessed spatial and temporal variations in pollinator importance by comparing honey bees to the seven most abundant unmanaged taxa in *Brassica rapa* ssp. chinensis fields in New Zealand. Results showed that unmanaged taxa were frequent visitors and provided equal or greater pollination services than honey bees in some years. The study suggests that unmanaged insects offer a safety net in case of honey bee population decline and recommends pollinator-specific farm management practices for optimising pollination services.

Garibaldi et al. (2013) studied the effects of wild insect and honey bee pollinators on crop yields in 41 agricultural systems worldwide. The authors found that fruit set was positively associated with flower visitation by wild insects in all systems, while honey bees had a significant effect on fruit set in only 14% of the systems. Wild insects were found to be more effective pollinators, with an increase in their visitation leading to twice as much enhancement in fruit set compared to an equivalent increase in honey bee visitation. The study suggests that integrated management of both honey bees and wild insect assemblages could enhance global crop yields.

Non-bee insects are important but understudied pollinators of global crops. Synthesizing 39 field studies, Rader et al. (2016) found that non-bees performed 25–50% of flower visits and provided similar pollination services to bees. Non-bee insects also increased fruit set independently of bee visitation rates, indicating a unique benefit. Unlike bees, non-bee insects are less reliant on natural habitat in the surrounding landscape, making their crop pollination services more robust to changes in land use. The findings suggest that non-bee insects provide a valuable service and potential insurance against bee population decline.

Howlett et al. (2017) found that honey bees were the most common visitors to kiwifruit flowers, but their abundance was lower during the afternoon. Other pollinators showed no significant differences in temporal abundances, suggesting the potential for complementarity between different pollinators in kiwifruit pollination.

Schmidlin et al. (2018) assessed insect flower visitation in native tree plantings on arable farms in Canterbury Plains, New Zealand, five years after planting. Native bees and honey bees were the most common visitors, followed by the large hoverfly and calliphorid flies. Most of the visitors were native and known crop pollinators, suggesting they may assist with crop pollination.

Stavert et al. (2018) measured pollination services for a mass flowering crop, pak choi Brassica rapa, at 12 sites with varying degrees of agricultural land use in New Zealand. Results showed that pollination services increased with agricultural expansion and were dominated by exotic fly species active throughout the day. The study suggests protecting and restoring natural habitats on or around farms to ensure continued sufficient crop pollination, but also acknowledges that where native species loss cannot easily be reversed, decisions to foster populations of beneficial exotic species are likely to maintain pollination service delivery. Land managers should identify the pollinator communities present on their farms and make decisions to support them accordingly.

Willcox et al. (2019) investigated the pollination services provided by wild visitors in multiple scenarios, including three crops within a single growing region, a single crop over 3 years, and different growing regions over multiple years. Across all three scenarios, eight wild visitor groups were shared, with three dominant pollinators. Specialisation increased with pollen deposition data, and node specialisation analyses indicated that site-specific factors were driving pollination patterns. Identifying shared taxa can help develop specific pollinator management strategies to optimise crop pollination services.

Rader et al. (2020) conducted a review of 105 global food crops that benefit from animal pollinators to compare the visitation and efficiency of crop-pollinating bees and non-bees. Of these crops, 77% were visited by both bee and non-bee taxa, with a total gross domestic product (GDP) value of US$780.8 billion. Non-bees, including flies, beetles, ants, wasps, and moths, visited a wide range of crops, and while limited efficiency data were available, non-bees were shown to provide valuable pollination services that require alternative habitat management practices to bees.

Földesi et al. (2021) compared single visit pollen deposition (SVD) among wild pollinators and the western honey bee using two assessment methods. The meta-analysis included data from 28 studies on 127 observations of 94 bee and 33 fly taxa. The researchers found that wild pollinators deposited more pollen per single visit than honey bees, with larger-bodied pollinators depositing significantly more pollen. There was no significant difference between the two methods of assessing SVD. The study highlights the need to further quantify the pollination effectiveness of non-bee pollinators, as most studies have focused on managed and wild bee species.

Howlett et al. (2021a) aimed to identify pollinators of *Actinidia chinensis* var. *deliciosa* 'Hayward' kiwifruit in New Zealand and found 11 species/taxa, including bees, flies, and a beetle. They then identified native and common exotic plant species that these pollinators interacted with and tailored regionally specific semi-natural plantings on kiwifruit farms to increase pollinator diversity. These plantings will be monitored in the future to determine their effect on pollinator diversity and crop yield over time.

Planting diverse native species on farms can increase the abundance and diversity of both non-bee and bee crop pollinators, leading to improved crop pollination. Howlett et al. (2021b) used existing literature to identify interactions between pollinators, natural enemies, and pests with native plants and crop species to design and establish plantings on three farms. The designed plantings supported 21 pollinating species, with 20 verified in observational surveys conducted 5 years post-establishment. The actual networks of non-bee pollinators were larger and more complex than expected, indicating that the plantings were particularly effective in supporting these interactions.

Pollination by animals is a crucial ecosystem service in New Zealand, providing a foundation for the country's agriculture-dependent economy (Newstrom-Lloyd 2013). Managed honey bees are the primary pollinators for most commercial crops in New Zealand, but in some cases, introduced bumble bees can be even more critical and are increasingly managed. New Zealand also has other introduced bees and a variety of solitary native bees that could be developed as managed colonies. Various insects and some vertebrates also contribute to pollination in both natural and agricultural ecosystems. However, New Zealand's reliance on managed honey bees exposes it to four major threats: diseases, pesticides, a limited genetic pool for breeding varroa-resistant bees, and a decline in floral resources (Newstrom-Lloyd 2013). In New Zealand, research has also been conducted on the impact of various factors on pollinator populations and crop pollination. For example, studies have explored the impact of pesticide use on pollinator health and behaviour and the importance of providing diverse floral resources to support pollinator populations (Clinch & Ross 1970; Devillers & Pham-Delègue 2002; Lester et al. 2014). Such studies aim to inform best practices for sustainable crop pollination and support the continued productivity of New Zealand's agriculture industry.

2.1.5 Greenhouse gas emissions and climate change

Globally, substantial reductions in greenhouse gas emissions are needed to limit the global temperature increase to well below 2°C above pre-industrial levels by 2100 (IPCC 2019). Agriculture accounts for 50% of New Zealand's gross greenhouse gas emissions with nearly 90% coming from ruminant livestock (MfE 2022b).

Greenhouse gas emissions on farms and orchards

Key on-farm and on-orchard sources of emissions include biogenic sources of:

(a) nitrous oxide (N_2O), a long-lived greenhouse gas in the atmosphere, from inputs of nitrogen to the soil from synthetic and organic fertiliser (including effluent), crop residues, animal excreta (urine and dung) from grazing livestock, ammonia deposition and leached or run-off nitrogen (so-called indirect source)

(b) methane, a short-lived gas, from ruminants, effluent, wetlands, and fuel and biomass burning.

Non-biogenic sources of CO_2 come from burning fossil fuels (petrol, diesel, gas and coal), and the breakdown of lime and urea applied to soil. Greenhouse gas emissions from the burning of horticultural trees and prunings are not currently considered in the national greenhouse gas inventory, while burning of stubble from three cereal crops and tussock land is considered (MfE 2022b). It might be possible to use the same type of approach used in the inventory (MPI 2022) to estimate N_2O and CH_4 emissions from burning orchard residue. But, this would require estimates of the volumes burnt and emission factors to estimate the losses. While CO_2 is emitted from the burning of trees and prunings, this would be expected to be offset by the uptake of CO_2 by trees and understorey. In many regions burning of residues is limited by Air Quality Regulations. For example, Environment Canterbury Regional Council says "While the fires are generally well-controlled, and this is a permitted activity under the regional plan, there can be a substantial impact in our community."(Environment Canterbury Regional Council 2023a).

N_2O is the primary greenhouse gas of concern on many orchards and cropping farms. However, in a range of farms and orchards grazing to manage understories or residues will lead to enteric CH_4 emissions from ruminants and these can become an important source of emissions due to the high warming potential of CH_4 relative to CO_2.

Nitrous oxide and CH_4 emissions are often converted to CO_2-equivalents or CO_2-e, accounting for the relative differences in warming effect of the greenhouse gases. According to the IPCC Fifth Assessment Report (AR5), N_2O has a global warming potential (GWP) 265 times greater than CO_2, while CH_4 has a GWP 28 greater than CO_2 over a 100 year time horizon (IPCC 2014). These values differ slightly from the GWP values from the Fourth Assessment Report (AR4); 298 and 25 for N_2O and CH_4, respectively (IPCC 2007). The New Zealand inventory still uses the AR4 values. Also, CO_2-e is the standard unit for carbon footprints.

Measurement and tools for estimating greenhouse gas emissions

Longer term changes in carbon stock from soil and plant biomass can be used to show if carbon is gained or lost in a farming system, or by using field scale measurements of CO_2 exchange (e.g. eddy covariance).

Measurement of greenhouse emissions on-farm or orchard is technically challenging. N_2O emissions may be measured using chambers on plots (Clough et al. 2020) or through field scale measurements (e.g. eddy covariance) (Laubach et al. 2023). Livestock CH_4 emissions can be measured using portable chambers enclosing the animal, exhaled air samplers or at the field scale by eddy co-variance (Laubach et al. 2016).

Due to the difficulty of measuring gas fluxes, simple accounting-based models are most widely used to estimate greenhouse gas emissions (IPCC 2006, 2019). This is the approach used for estimating New Zealand's agricultural emissions (MfE 2022b). In the national inventory approach, N_2O is estimated from inputs of nitrogen in synthetic and organic fertiliser, crop residue and soil mineralisation. These are so-called direct N_2O emissions. Indirect N_2O emissions are also estimated from deposition of volatilised ammonia and from leached and runoff nitrogen. Some N_2O and CH_4 is emitted from burning of residues. Nitrous oxide emissions from the decomposition of crop residues are only reported for a limited number of crops; only 14 "key" arable and vegetable crops are reported (MfE 2022b). This excludes all the perennial fruit and nut crops and most of the vegetable crops (MPI 2022). Above ground residues left on the soil and root material below ground decompose and release nitrogen that can then be emitted as N_2O directly from the soil or indirectly from leached or runoff nitrogen. The emission factor for crop residues (namely EF1) is the same as the emission factor used for non-urea nitrogen fertilisers. Following the approach used in the inventory, crop residues of vegetable crops that remain in the paddock, residues of fruit and nut trees left on the orchard floor (e.g. prunings or thinning), and understory residues (e.g. left after mowing) should be considered as direct and indirect sources of N_2O. However, there is sparse information on the amounts of nitrogen returned in residues and even less knowledge on whether the emission factor (also the same as non-urea nitrogen fertiliser, EF1) is appropriate for the range of residues and their management. In the absence of better information it is assumed that the emissions factor is appropriate for the inventory. Nitrous oxide emissions are also estimated in the national inventory from net soil nitrogen mineralisation, i.e. the difference between gross soil nitrogen mineralisation and nitrogen that is immobilised in the soil. This is done at a national level for all New Zealand cropland, i.e. does not account for any difference between crop or crop system. Emission factors and calculation methods are published routinely by MPI (MPI 2022).

A variety of N_2O and CH_4 mitigation tools are available or being explored (Reisinger et al. 2017) and as they become available should be applied where appropriate in farm and orchards. For most vegetable growers and orchardists, mitigation of N_2O emissions will be most important, unless grazing is used in their systems. Most mitigations for N_2O are designed to minimise the amount of soil minerals available for microbial processes, particularly in the form of NO_3^- (e.g. nitrification inhibitors, but also through careful management of nitrogen inputs). Most of the mitigation measures aimed to reduce NO_3^- leaching will have a similar effect on N_2O emissions. Other mitigation approaches could include improving aeration, drainage, excess watering, and avoiding compaction. Because most of farm and orchard emissions rely on estimation of their emissions using simple calculations, the benefits of mitigation technology, i.e. reduction in emissions, will need to be proven to be included in greenhouse gas emission calculators. Examples where this has happened elsewhere is the use of urease and nitrification inhibitors (specifically dicyandiamide, DCD) in the national inventory (Clough et al. 2009; Saggar et al. 2012). Unfortunately, DCD is no longer used as a mitigation because of issues with detection in milk.

He Waka Eke Noa and Greenhouse gas emissions tools in New Zealand

By 31 December 2022 every farm in New Zealand (enterprises over 80 ha) was required to document its annual biogenic greenhouse gas emissions. Then by 1 January 2025 every farm will need to have a farm plan to estimate and manage their emissions. By the same time an on-farm emission pricing system will be in place. There are 11 approved greenhouse gas emissions tools available to growers as of January 2023 (He Waka Eke Noa 2023a). For example, Horticulture New Zealand (HortNZ) has produced a N_2O emissions spreadsheet developed by and available from MPI (HortNZ 2023). This tool does not include calculations of CH_4 emissions. Unless vegetable farmers or orchardists have animal grazing, they will only need to account for emissions due to fertiliser application. This means that emissions from residues are excluded from He waka eke noa. All these tools are based on greenhouse gas inventory type calculations, and do not take into account interactions with environmental factors. Soil physical properties (e.g. soil water content, aeration, temperature), and amount of soil inorganic nitrogen affect emission timing and rates. For example, soil compaction from wheel traffic in crops and livestock treading can increase N_2O emissions by up to 10 times (Thomas et al. 2004b; Thomas et al. 2008; Hu et al. 2021).

Accounting for greenhouse gas emissions in farming

It is possible to estimate non-biogenic CO_2 emissions from on-farm or orchard operations, such as CO_2 emitted from fuel combustion for machinery, heaters and driers or irrigation pumps. MfE has published appropriate data and methods to calculate these emissions (MfE 2022a). While as described above, it might be possible to account for greenhouse gas emissions from burning of plant residues (MPI 2022).

Quantifying carbon sequestration and LCA protocols

While there is an interest by growers to account directly for carbon sequestration on farms and orchards, the ability to quantify this is not yet available.

In 2008–09, there were a range of MPI-resourced projects that used Life Cycle Assessment (LCA) to quantify the cradle-to-grave emissions from primary production systems (see more detailed introduction of LCA in Section 2.3.3.2). In horticulture, these studies covered kiwifruit, wine, apples, and berryfruit (i Canals et al. 2006; Herath et al. 2013; Müller et al. 2015; De Silva & Forbes 2016). In 2021, MPI received a report on the updated LCA protocols and the footprints for apples, kiwifruit, and wine (McLaren et al. 2021). According to the report, there has been a reduction in the LCA footprint for apples exported from New Zealand by 13% between 2008 and 2019. Similarly, there was a 24% reduction in the LCA footprint for kiwifruit delivered to a German retailer during the same time period (McLaren et al. 2021).

Measuring greenhouse gas emissions and metrics

Table 5 lists metrics and attributes for the measurement and determination of greenhouse gas emissions at a farm/orchard/vineyard level in New Zealand. To evaluate the total greenhouse gas emissions at a farm scale, three main greenhouse gases (CO_2, N_2O, and CH_4) need to be considered. They can be either measured directly using small chambers or field scale measurements or estimated indirectly from agricultural inputs data. For example, N_2O can be estimated using nitrogen input activity data (e.g. fertiliser, residue return, and animal excreta input) and emission factors. Activity data may be available from growers' information and/or estimated using tables and emission factors for New Zealand conditions. In addition, greenhouse gas emissions can be also produced outside of the farm but are associated with producing materials for farming use (e.g. fuel, electricity, fertiliser, and agrichemical product) or on-farm activities (e.g. mulching, harvest, and irrigation).

Practicable metrics that provide evidence of reduced soil mineral nitrogen should be encouraged as this would be expected to reduce the risk of both N_2O emissions and NO_3 leaching. For example, this could be through using a nitrogen balance tool, soil mineral nitrogen testing, targeted use of urease and nitrification inhibitors to reduce losses from fertilisers, management of residues to better synchronise soil supply with plant demand.

Table 5. Metrics and attributes for the measurement and determination of **greenhouse gas emissions** at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons
Nitrous oxide (N_2O) emissions	N_2O fluxes: Direct measure	N_2O soil gas fluxes, measures of soil physical and biochemical conditions. Expressed as N_2O-nitrogen (N) kg/ha/year or Carbon dioxide (CO_2)-e kg/ha/year	Direct measurement by chambers or agrometeorology methods (eddy covariance)	Difficult	Suited to research applications to improve emission quantification, understanding of biophysical processes for improved models, developing mitigation technologies Direct measure of N_2O emissions Requires high temporal and spatial frequency measurements to produce robust total emissions, and specialised equipment and skilled users are required
	N_2O fluxes: Indirect estimates	Activity data: fertiliser, residues, animal excreta N inputs; ammonia deposition and leached or run-off N) Environmental data: climate, soil temperature and soil water content and emission factors. Expressed as N_2O-N kg/ha/year or CO_2-e kg/ha/year	Growers (for materials and activities), Ministry for Primary Industries (MPI) guide[1]	Some information can be provided by growers. Other information is from literature or support tools	Relatively simple using Intergovernmental Panel on Climate Change (IPCC) rules compared with direct measurement, the IPCC approach is already used in various grower/grower tools including Overseer, aligned to the national inventory methods Ignores on site environmental conditions that are important drivers of emissions
Methane (CH_4) emissions from grazing livestock	Enteric CH_4 fluxes Direct measure	Animal or field scale CH_4 fluxes. Expressed as CH_4 kg/ha/year or CO_2-e kg/ha/year	Direct measurement by chambers or agrometeorology methods (eddy covariance)	Difficult, and highly specialised technique	Suited to research applications to improve emission quantification, understanding of biophysical processes for improved models, developing mitigation technologies Direct measure of CH_4 emissions requires high temporal and spatial frequency measurements, and specialised equipment and skilled users
	Enteric CH_4 fluxes Indirect estimates	Feed intake estimates and relevant emission factors, and environmental data. Expressed as CH_4 kg/ha/year or CO_2-e kg/ha/year	MPI inventory guide	Some information can be provided by growers. Other information is from literature or support tools	Relatively simple compared with direct measurement, approach is already used in various grower/grower tools including Overseer, aligned to the national inventory methods; Based on relatively simple modelling, and ignores on site environmental conditions that are important drivers of emissions
CO_2 emissions from lime and urea	CO_2 Indirect estimates	Applied amounts of lime and urea, activity data, environmental data, and emission factors. Expressed as CO_2 kg/ha/year	MPI inventory guide	Easy as data are already collected	Relatively simple compared with direct measurement, approach is already used in various grower/grower tools, aligned to the national inventory methods Based on relatively simple modelling and ignores on site environmental conditions that are important drivers of emissions.
CO_2 fluxes	Net primary production i.e. whether the orchard is a	Above canopy CO_2 fluxes. Expressed as CO_2 kg/ha/year	Direct measurement by chambers or agrometeorology methods (eddy covariance)	Difficult	Direct measure of the net change in carbon (C), and suited to research applications to improve carbon flux quantification, understanding of biophysical processes for improved models, developing mitigation technologies, a research approach

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons
	net source or sink of C.				Requires highly specialised equipment and skilled users
	Biomass	Land area, plant density, and biomass per plant time. Expressed as t C/ha/year	Direct measurement	Difficult and depends on long-term measurement. Requires accurate measurements and allometric relationship developed for perennial crops	Can be used to indicate how much C is stored in biomass. suited to research applications to improve carbon flux quantification, understanding of biophysical processes for improved models, developing mitigation technologies Requires skilled techniques, difficult to estimate especially for below ground biomass, and need to be measured over a long timescale
Other CO_2 from non-biological sources emitted on farm and orchard	CO_2 emitted from: Fuel use for farm and orchard operations: Diesel, petrol, LPG, Electricity use	Diesel, petrol, LPG (e.g. tractor, spreader, sprayer, harvester, on-site processing and drying); Litres used or estimates based on time, machinery fuel consumption rates, and number of passes and area; Electricity use (e.g. irrigation pumping, irrigation operations, on-site processing and drying; Kilowatt hours used, the % used on farm); and emission factors. Expressed as CO_2 /ha/year	Growers (for materials and activities), MPI and Ministry for the Environment (MfE)[2] guides). Fuel emissions factors for NZ are provided and updated by MfE	Variable depending on records available and appropriate emission factors. Available from growers and literature	Greenhouse gas emissions outside of farms due to the use of materials and agricultural activities on farms can be considered Inaccuracies due to assumptions required

1 Ministry for Primary Industries 2022. Methodology for calculation of New Zealand's agricultural greenhouse gas emissions. Version 8. Wellington: Ministry for Primary Industries,
2 Ministry for the Environment 2022. Measuring Emissions: A Guide for Organisations: 2022 Detailed Guide Wellington Ministry for the Environment.

Nitrous oxide (N_2O) emissions and effects of management practices

There have been no measurements of gaseous nitrogen losses under perennial horticulture in New Zealand (Gentile et al. 2022). Relevant studies are mainly based on inventory data (McLaren et al. 2021). We know of only three field studies of N_2O emissions from vegetable crops (onions and potatoes) in New Zealand (van der Weerden et al. 2000; Thomas et al. 2004a). The paucity of studies reflects the emphasis on research to quantify greenhouse gas emissions from animal agriculture that dominate the New Zealand agricultural greenhouse gas inventory. An additional factor is the relative difficulty of making chamber gas measurements within crops compared to relatively short pastures.

The key biological processes leading to N_2O emissions are denitrification and nitrification. Denitrification is a largely anaerobic process strongly influenced by the degree of saturation of the soil. Saturation affects both the aeration of the soil and the diffusion of gases into and out of the soil. Nitrous oxide is an intermediary product of denitrification with environmentally benign dinitrogen being the terminal product. Whereas nitrification is an aerobic process that tends to produce smaller N_2O emissions. As well as the degree of aeration, key controls of emissions are the availability of soil inorganic (or mineral) nitrogen and carbon that are substrates for the soil microbes.

Soil and plant management activities that affect emissions include synthetic and organic fertilisation events, cultivation, spraying off and leaving fallow, residue management, machinery traffic and animal grazing.

Fertiliser inputs, and decomposition of crop residues and mineralisation of soil organic matter are important drivers of N_2O emissions in vegetable crops. As will the effects of tillage, machinery compaction and irrigation (Thomas et al. 2004a, Thomas et al. 2019, Vogeler et al. 2019). As noted for nutrient leaching losses, the relatively large amounts of nitrogen released from the decomposition of crop residues and soil mineralisation may be as important as nitrogen fertiliser inputs for producing N_2O for some fruit crops and vegetable crop rotations.

A meta-analysis of N_2O emissions in perennial fruit trees found annual emissions ranged from -0.116 to 26 kg N_2O-N ha^{-1} y^{-1} (Gu et al. 2019). Cumulative N_2O emissions also increased linearly with nitrogen fertiliser rates. Interestingly, N_2O emission factors uncorrected for background emission were 25% higher with the use of organic amendments than those with the use of synthetic fertilisers (Gu et al. 2019). Similarly, Kramer et al. (2006) found that N_2O emissions were the same between organic and conventional apple orchards in Washington State, USA, but that dinitrogen (N_2) losses were greater from the organic orchard, indicating larger total gaseous nitrogen losses. These results suggest that increased carbon availability with organic fertilisers may stimulate denitrification N losses. In contrast, Fentabil et al. (2016) found that surface-applied wood mulch reduced N_2O emissions in a Canadian apple orchard even though soil labile organic carbon increased.

Gaseous emissions from apple orchards show high temporal and spatial variability in the international literature. N_2O emissions are higher during the summer growing season in climates without freeze-thaw cycles (Riga & Charpentier 1999; Swarts et al. 2016) and pulses of N_2O occur after nitrogen fertiliser applications and summer rainfall or irrigation (Pang et al. 2009; Fentabil et al. 2016). For example, Swarts et al. (2016) found that N_2O emissions were 50% higher in summer (maximum 5.27 g N_2O-N ha^{-1} day^{-1}) than winter (maximum 2.47 g N_2O-N ha^{-1} day^{-1}) across the four trial orchards (Southern Tasmania: Lucaston-apples, Lower Longley-cherries, Northern New South Wales: Orange-apples and Young-cherries). Pang et al. (2009) found N_2O emissions increased closer to the tree row and band of fertiliser application in an apple orchard in China, whereas Swarts et al. (2016) found N_2O

emissions in Australian apple orchards were 40% greater in the grassed alleyway than the tree line, which may have been due to higher carbon inputs or poorer soil structure in the alleyway. This is in consistent with Hu et al. (2021) who found that wheel traffic compaction increased N_2O emissions by 19% to 1300% in arable land. It is recommended that optimising nutrient use efficiency with improved drainage and a reduction in soil compaction in the inter-row will facilitate further mitigation of N_2O emissions (Swarts et al. 2016).

Irrigation was also found to affect N_2O emissions. For example, higher emissions of N_2O were observed under drip irrigation (1.6±0.7 kg N_2O-N ha^{-1} y^{-1}) compared with micro-sprinkler irrigation (0.6±0.3 kg N_2O-N ha^{-1} y^{-1}) in almond orchards because a more anoxic, waterlogged bulb is developed under drip irrigation (Alsina et al. 2013), and subsurface drip irrigation reduced N_2O emissions compared with surface drip irrigation in olive orchards (Quiñones et al. 2007). In an orchard located at Egirdir Fruit Research Institute Isparta-Turkey, Ekinci et al. (2020) found that the value of total greenhouse gas emissions of organic production was significantly ($p<0.01$) lower than conventional production (1344 vs 1476 kg CO_2-eq ha^{-1}).

2.1.6 Weed, pest and disease management

Weed, pest, and disease control is important for maximising productivity and profitability in both organic and integrated management systems. For example, the tomato potato psyllid invaded New Zealand in the summer of 2005–06 and spread throughout much of New Zealand by April 2009 (Teulon et al. 2009). It was estimated that the economic effects of this insect and disease in the 4 years it had been in New Zealand was millions of dollars in terms of increased management costs, crop losses and loss of export markets, which brought a serious challenge to the development of integrated pest management in greenhouse crops, outdoor tomatoes, and potatoes (Teulon et al. 2009).

Currently, weeds are mostly controlled using integrated control, a combination of chemical (e.g. herbicides), biological (e.g. use of insects, for example, gorse spider mite), and cultural methods (e.g. cultivation, mulching, livestock grazing, and hoeing) (Te kura 2023b). Similarly, pests and diseases can be controlled by chemical (e.g. pesticides, fungicides, bactericides, poison baits or traps, and soil sterilisation), biological (e.g. use of living organisms such as predators or parasites) or cultural methods (e.g. quarantine, crop rotation, using resistant plant varieties, good management, and work practices). For example, compounds of metals such as copper and zinc are commonly used as fungicides and bactericides in fruit trees. Now, integrated pest management by combining chemical, biological, and cultural methods are widely pushed and adopted to control pests and diseases across horticultural land uses (Te kura 2023a). Each method has its own advantages and disadvantages. While both biological and cultural methods are more socially and environmentally acceptable, chemical methods have the advantages of quick-acting and cost-effective. However, using chemicals to control weeds, pests, and diseases had the following issues: (1) target agripests can be resistant to the chemicals used to manage them; (2) safety of food and fibre products can be threatened by the chemicals; (3) potential health impacts of chemicals on workers and their communities; and (4) environmental damage to land, water, flora, and fauna. Annually, approximately 3400 tonnes of pesticide active ingredients are used in New Zealand Agriculture (Martine't Mannetje 2020). While they are designed to be toxic to pests, they may also affect non-target organisms including humans. It was estimated that 4–26% of total active pesticide ingredients sprayed in New Zealand are classified as suspected human carcinogens (Martine't Mannetje 2020). The suspected carcinogen weight was highest for fungicides (72–540 tonnes), followed by herbicides (60–200 tonnes) and insecticides (16 tonnes) (Martine't Mannetje 2020). Therefore, it is important to consider relevant standards such as the maximum residue level (MRL) and the threshold point of spray when conducting weed and pest control.

Table 6 lists metrics and attributes for the measurement and determination of weed, pest, and disease management at a farm/orchard/vineyard level in New Zealand. Usually, the spray amounts of herbicides, pesticides, fungicides, bactericides, growing regulator, adjuvants, and pollination sprays can be measured by the number of sprays, the type of spray, the area that the spray is applied to, and the spray rate (e.g. active ingredient [a.i. ha^{-1}]). When applying sprays, it's important to consider spray efficiency, which is influenced by factors such as the type of nozzles used, pressure rates, the stage of canopy growth, spray volume, and canopy training system. All these data are easily available from growers. They are useful to quantify the total amount of spray, but they may not accurately reflect the efficiency of weed, pest, and disease control. The environmental performance and effects are difficult to quantify and need to be further explored in the future. Furthermore, the spraying time relative to pest life cycle (e.g. growth, maturation, and reproduction) and crop growth stages is critical to the pest control. In addition, plastic film is widely used to supress weeds or increase the intensity of light within the tree canopy for improving fruit colour. However, this also potentially results in plastic, micro- or nano-plastic pollution in soils, which may enter the food chain and endanger human's health (Qadeer et al. 2021). However, related studies in New Zealand horticulture are lacking.

Table 6. Metrics and attributes for the measurement and determination of **weed, pest and disease management** at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
Weed management	Spray amount of herbicides (a.i.)	Number of sprays spray timing, type, a.i./ha, area (ha) treated, maximum residue level (MRL), threshold level, spray efficiency (e.g. types of nozzles, pressure levels, canopy growth stage, spray volume, canopy training system)	Growers, Ministry for Primary Industries (MPI)	Spraying activities data are easily available from growers; associated standards (MRL, threshold level) are available from MPI	The amount of a.i. for total herbicides and classes of herbicides can be accurately quantified may not accurately reflect the efficiency of weed control and environmental impacts	Spraying timing relative to crop growth stages is crucial; MRL varies with country
	Plastic and nano-plastic content in soil	Plastic type, weight or area of plastic used	(See above)	Difficult to predict the plastic and nano-plastic content	Plastic use can be accurately quantified; hard to quantify the plastic (including micro, nano) content and distribution in soils	More will be discussed in section 2.1.8.6
Pest and disease management	Spray amount (a.i.) of pesticides (e.g. fungicides, bactericides)	Number of sprays spraying timing, type, a.i./ha, area (ha) treated, maximum residue level (MRL), threshold level, and spray efficiency	Growers, MPI	Spraying activities data are easily available from growers; associated standards (MRL, threshold level) are available from MPI	The amount of a.i. for total pesticides and classes of pesticides can be accurately quantified may not accurately reflect the efficiency of weed control and environmental impacts	Heavy metals will be discussed in section 2.1.8.4; spraying timing relative to pest life cycle and crop growth stages is crucial; MRL varies with country
	Adjuvants amount	Number of sprays, spraying time, type, a.i./ha, area (ha) treated, threshold level, and spray efficiency	(See above)	(See above)	The amount of a.i. for total adjuvants and classes of adjuvants can be accurately quantified may not accurately reflect the efficiency of weed control and environmental impacts	Used to improve disease management; spraying timing relative to pest life cycle and crop growth stages is crucial; MRL varies with country
	Natural enemies	Number of natural enemy species in an area, number of individuals per species	Direct measurement	Not easily available	Total number of natural enemies can be quantified; hard to quantify their impacts	Associated with biodiversity; natural enemies are often introduced to greenhouses for pest control
	Spray amount (a.i.) of growing regulators	Number of sprays, spraying timing, type, a.i./ha, area (ha) treated, maximum residue level (MRL), threshold level, and spray efficiency	Growers, MPI	Spraying activities data are easily available from growers; associated standards (MRL, threshold level) are available from MPI	Spray amount and its classes can be accurately quantified; its impacts on growth and environment are hard to quantify	Spraying timing relative to crop growth stages is crucial; MRL varies with country

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
Pollination	Pollination spray amount	Number of pollinating sprays (also called blossom set sprays or blossom hormone sprays, e.g. tomato and blossom set spray), spraying time, type, P/ha, maximum residue level (MRL), threshold level, and spray efficiency	(See above)	(See above)	(See above)	Used for increase the quantity of blossoms and to speed up fruit development, but not actually pollinate the vegetable plant they are used on; spray timing relative to crop growth stages is crucial; MRL varies with country
	Pollinators	Number of pollinator species in an area, number of individuals per species	Direct measurement	Not easily available	Total number of pollinators can be quantified; hard to quantify their impacts on growth	Associated with biodiversity

2.1.7 Heavy metals

Heavy metal and impacts

Heavy metals are a group of metallic elements that have a high atomic weight and density. They include elements such as iron (Fe), lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), manganese (Mn) copper (Cu), nickel (Ni), and zinc (Zn). Treated-timber contains Copper Chromium Arsenate (CCA)-based preservatives of copper, chromium and arsenic to prolong timber life in the environment. Treated timber is used as structural supports for horticultural canopies. These metals are toxic and can accumulate in living organisms, leading to harmful effects on health and the environment. Toxic metals are a subset of heavy metals that have particularly harmful effects on living organisms even at low concentrations. These include Pb, Hg, Cd, and As, which can cause serious health problems even in small amounts. In horticulture, heavy and toxic metals can be present in soil, water, and fertilisers, and can accumulate in plants, posing risks to human health and the environment. While some metals are essential for plant growth, such as iron and zinc, high concentrations of toxic metals in soil and plants can be detrimental.

Regulations to manage heavy metals in horticulture

In New Zealand, there are guidelines and regulations in place to monitor and manage heavy metal concentrations in horticulture. MPI sets maximum permissible concentrations for heavy metals in soil and water, and growers are required to test their soil and water regularly to ensure compliance. For example, in New Zealand, the maximum permissible rates of lead in soil for horticulture is 300 milligrams per kilogram (mg/kg) of soil, while the maximum rate of cadmium is 1 mg/kg of soil. Exceeding these amounts can lead to restrictions on crop growth or even legal action. Overall, while low rates of some metals are acceptable in horticulture, high rates of heavy metals can have serious consequences for human health and the environment, therefore, it is crucial to monitor and manage their presence carefully.

Cadmium management in New Zealand horticulture

Cadmium (Cd) is a naturally occurring heavy metal found at low concentrations in air, water, and soils. It occurs naturally in phosphate rock, which is used to make superphosphate fertiliser in New Zealand. While ongoing use of phosphate-based fertilisers can lead to a build-up of Cd content in soils, Cd content in New Zealand soils is still relatively low. To address concerns about Cd rates in fertilisers, the New Zealand fertiliser industry adopted a limit for Cd concentration of 280 mg /kg in fertilisers in the late 1990s, with current average concentration at approximately 180 mg Cd/kg fertiliser. Cd can enter the food chain through plants that are eaten by animals, and naturally high concentrations of Cd are found in some shellfish and crustaceans. Soil monitoring scheme is important to maintain productivity and to prevent high concentrations of Cd accumulation in soils. Additionally, MPI has been monitoring Cd rates in food as part of the New Zealand Total Diet Study. The amount of Cd present in the diet of the average New Zealander falls within World Health Organisation guidelines and considerably below threshold that will adversely affect human health (MPI 2023b).

The Cadmium Management Group and its members have produced reports and reviews to help manage Cd concentrations/prevent Cd contamination in New Zealand (MPI 2023c). These are reports related to managing and monitoring Cd concentrations in agriculture and horticulture in New Zealand (Cadmium Management Group 2019). The Cadmium Management Strategy outlines activities to lower Cd content in food, soils, and fertiliser (Cadmium Management Group 2019), while the Tiered Fertiliser Management System aims to limit Cd accumulation in soils (MPI 2023f). The Status of Cadmium in New Zealand Soils report provides updated data on soil Cd concentrations and recommends future soil sample collection strategy (Fertiliser Association 2023), while Cadmium in New Zealand Agriculture summarises the risks of cadmium in agricultural soils (MPI 2023a).

Metrics for heavy metals

Agrichemical sprays or fertilisers are widely used to control pest and disease or stimulate plant growth in horticulture. However, agrichemicals usually contain heavy metals or toxic metals (e.g. cadmium, zinc, copper, chromium, lead, and arsenic) which can potentially contaminate the environment (air, soil, water, and plant). Therefore, the application of approved agrichemicals in a way that gives the highest possible spray retention on the target is important for minimising contamination of the environment. In the fruit system, factors affecting spray retention include canopy growth stage, spray application volume, and canopy training system (New Zealand Apples & Pears 2023) (Table 7). Spray retention varies greatly between different sprayer setups (especially nozzle arrangement and sprayer air output volumes) for different canopy training systems. Growers should spray when the canopy leaves up and after full bloom (i.e. more than 50% of the total leaf area for the season is present). The retention from a well-set-up sprayer can be as high as 90% of the applied spray volume. Use of a typical concentrate spray application method will deposit 10–20% more active ingredient on average per square centimetre of leaf or fruit surface area than a typical dilute spray application. When air blast spray is applied, it is better to ensure spray deposition in dense hedge row canopies to achieve penetration into the canopy and not just exterior dispersal. Maximising “spray retention” on the target canopy can avoid spray losses by drifting onto the ground within sprayed blocks. Any insects or disease can develop resistance after heavy reliance on a single type of insecticide or fungicide. Therefore, the guidelines must be followed to ensure effective and stable control of insects and diseases.

Table 7. Metrics and attributes for the measurement and determination of **heavy metal** contamination at a farm/orchard/vineyard level in New Zealand.

Metrics	Primary attributes	Secondary attributes	Likely sources of data	Ease of sourcing data	Pros and cons	Notes
Heavy metal contamination	Heavy metal (e.g. cadmium, zinc, copper, chromium, lead, arsenic) spray amount	Spray substances, chemical composition and concentration, spray time, and dosage	Growers	Easily available	Spray amount of various heavy metals can be accurately determined; the spatial distribution in plant and soil and their environmental impacts are hard to quantify	Please refer to (MPI 2023e) and (MPI 2023c) for Cadmium monitoring and research in New Zealand
	Spray method	Coverage, evenness, and sprayer setups (i.e. nozzle arrangement and sprayer air output volumes)	(See above)	(See above)	(See above)	
	Spray retention	Canopy growth stage, spray application volume, and canopy training system	(See above)	(See above)	(See above)	
	Spray drift	If low drift nozzles are used, weather condition during and immediately after spray	(See above)	(See above)	(See above)	Weather conditions can be used to estimate the risk of spray drift
	Heavy metal concentrations in soil and plants	The states of heavy metals: total or extractable forms; Heavy metal concentration	Direct measure	Not easy, need sampling and lab analysis, and some analyses are expensive		

Heavy metals accumulation in horticulture

Soil contamination by toxic metals is a great environmental concern, because of its adverse effects on soil quality and the potential metals' bioaccumulation in plants, in particular those plants intended for human consumption (Squadrone et al. 2020). Accumulations of copper or zinc in orchard soils and fruit trees resulting from the application of Cu/Zn-based fungicides or pesticides as well as fertilisers and manure (Alloway 2012) have become recent research hotspots (Jones & Jarvis 1981). Foliar fungicides, e.g. the copper-based Bordeaux mixture ($Ca(OH)_2 + CuSO_4$) and zinc-based mixtures, such as those with the active ingredient Mancozeb ($C_4H_6MnN_2 S_4 \times Zn$), are still applied globally throughout the year worldwide. Several factors contribute to accumulation of Cu and Zn fractions in orchard soils, especially in the upper soil layers. They include unidirectional fungicide applications, rainfall washing off Cu/Zn from leaf surface, the deposition of senescent leaves and pruned branches, the cycling of Cu and Zn by species of ground cover plants that co-inhabit the orchards, a low transfer of Zn and Cu to fruits, and an absence of soil disturbance between orchard rows (Fernández-Calviño et al. 2010; Mackie et al. 2012; Ruyters et al. 2013). The accumulation/high concentration of Cu and Zn in agricultural soils (inorganic spray is one source) can deteriorate soil quality and increase phytotoxicity. Cu and Zn can be either micronutrients or toxic elements, but whether these effects are positive or negative depends on their concentrations in the soil and plant tissues, and their geochemical forms in the soils (Temminghoff et al. 1997). The heavy metal contamination in different vegetables has been reviewed worldwide (Suruchi & Pankaj 2011). Silva et al. (2019) evaluated the availability of Cd, Mn, Cu, Pb, Ni and Zn in the soil of five agricultural areas compared with the soil of adjacent native forests in Brazil, to determine the risk of soil, water, and plant contamination. Their study revealed that intensive agricultural inputs resulted in an increase in total Mn, Cu and Zn concentrations; Cd, Ni and Pb concentrations exceeded the values established by the National Environment Council for human consumption and irrigation water. To prevent the excessive heavy metals accumulation in the food chain, it is necessary to constantly execute pollution control of hazardous materials in soils and plants.

Several studies conducted in New Zealand, mostly in the Bay of Plenty, investigated soil heavy metals accumulation following chemical spraying in kiwifruit orchards. For instance, total recoverable As, Cd, Cr, Cu, Ni, Pb, and Zn at 20 kiwifruit orchards (12 sites) from Western Bay of Plenty were measured (Guinto et al. 2012). The results indicated that for heavy metals, the mean values of the 2012 samples were below the environmental guideline values based on the 2003 NZ Biosolids Guidelines. However, Cd content in 15% of the sampled orchards (3 out of 20 orchards) exceeded the 1 mg/kg (environmental guideline value). There were no significant increases in the concentrations of As, Cd, Cr, Ni and Pb. Conversely, Cu and Zn content in the soil showed significant increases over the 3-year period (Guinto et al. 2012). In Auckland, Tasman, and Waikato regions of New Zealand, the routine historical use of agrichemicals has resulted in elevated concentrations of heavy metals and pesticide residue, in particular As, Cd, Cu, and Pb, as well as Sigma DDT in horticultural soils (e.g. orchards, vineyards and market-gardens) over the 3-year period (Gaw et al. 2006).

2.1.8 Mahinga kai

Mahinga kai or mahika kai (food procurement) literally means “to work the food”” and relates to the traditional value of natural resources (including plants, birds, and other animals), their ecosystems and the resources that sustain life, as well as the practices involved in producing, procuring, and protecting these resources (Environment Canterbury Regional Council 2023b). These values have been identified within the National Objectives Framework for Freshwater Management (Collier et al. 2017) and the National Policy Statement for Freshwater Management 2020 (MfE 2020a). These values connect with access to clean and healthy kai, securing food in a sustainable way, and considering our future generations (Lyver et al. 2017).

Mahinga kai areas are likely to be those special areas on a property that are already being actively taken care of for their environmental or biodiversity significance; but it could also be for things that you were not aware of, the small and little things. Mahinga kai refers to numerous species and inter-relationships rather than something specific. It includes things such as species, natural habitats, materials, and practices used for harvesting food, and places where food or resources are, or were, gathered. Therefore, everyone has a part to play in protecting and enhancing mahinga kai, as an important part of sustainable environmental management.

Growers who require land use consents to farm also have a responsibility to address mahinga kai. They need to be aware of the mahinga kai values and risks on their farms, and address these when applying Industry-agreed Good Management Practices to protect mahinga kai species and habitats when waterways are managed or cleared and sustain mahinga kai through management of remnant native vegetation and wetlands. Contaminants and environmental stressors likely to be affecting some important freshwater mahinga kai species such as tuna (eel), īnanga (whitebait), kākahi (freshwater mussel), koura (freshwater crayfish), and wɑ̄takirihi (watercress), has been reviewed (Collier et al. 2017). In that report, the following guidance are provided on how to relate existing guidelines and regulations to freshwater invertebrate and fish species traditionally used for food gathering (Collier et al. 2017):

- The Australian and New Zealand Environment and Conservation Council (ANZECC) (2000) water quality guidelines for physical and chemical attributes aquatic life
- Selected international water quality guidelines (e.g. United States Environmental Protection Agency [USEPA], Environment Canada, Organisation for Economic Co-operation and Development [OECD])
- Human health information for collection and consumption of aquatic foods
- The National Policy Statement for Freshwater Management (NPS-FM) and the National Objectives Framework (NOF).

The report by Collier et al. (2017) can be used to support discussion on food abundance and safety of mahinga kai, and promote steps to ensure appropriate standards are set for clean waterways and customary resources under the NPS-FM and ANZECC (2000). Various mitigation practices for maintaining and enhancing water quality on dairy farms were scored for different attributes including effectiveness of reduction in contaminant loss for nitrogen, phosphorus, sediment and *Escherichia coli*., cost-effectiveness in terms of the quantity of contaminant that could be mitigated for nitrogen, phosphorus, sediment and *E. coli*., capital cost to the farm business is provided for “established” mitigations, and greenhouse gas emissions, along with mahinga kai values (Macintosh & Dairy 2021). In the horticulture sectors, research is required to understand the potential sources of chemical contamination and nutrients from horticultural activities on water quality and mahinga kai (e.g. eutrophication, decreased visibility and dissolved oxygen rate, bioaccumulation of contaminants in animal tissues, loss of species and habitats). As mahinga kai is closely related to the ecosystem environment, previous metrics related to water quality and biodiversity can be linked to mahinga kai as well.

Mahinga kai and Tikanga Māori are intimately linked in Māori culture. While mahinga kai refers to the traditional Māori practices of managing and utilising natural resources for food, medicine, and other needs, Tikanga Māori refers to the customs, protocols, and traditional practices that guide Māori ways of living and interacting with the natural world (Mead 2016). In Māori culture, mahinga kai and Tikanga Māori are interconnected in a holistic way. The principles of Tikanga Māori guide the sustainable practices of mahinga kai, ensuring that resources are used in a way that is respectful, balanced, and in harmony with the natural world. For example, Tikanga Māori values such as kaitiakitanga (guardianship) and manaakitanga (hospitality) inform how Māori manage natural resources like forests, rivers, and oceans. Mahinga kai and Tikanga Māori also have a spiritual aspect, as they are tied to the Māori worldview of interconnectedness between all living things. Mahinga kai practices are often accompanied by karakia (prayers) and other rituals to acknowledge and give thanks to the spiritual guardians of the land and sea. Tikanga Māori also emphasises the importance of maintaining strong relationships with one's ancestors and the natural world. Overall, mahinga kai and Tikanga Māori are integral parts of Māori culture, reflecting a deep respect and connection to the land, sea, and natural environment. These practices have been passed down through generations and continue to play an important role in the lives of Māori communities today. Therefore, in addition to the physical KPIs for water quality and biodiversity which is related to the environmental sustainability, other indicators such as cultural knowledge and transmission, community participation, food security and sovereignty, and economic viability should be considered to mahinga kai.

2.1.9 Other environmental areas of interest

Waste management

Waste management is a critical element to the sustainable production of fruit and vegetables (HortNZ 2021). HortNZ proposed a waste strategy for the New Zealand horticultural industry in which a circular economy vision was supported (HortNZ 2021). Food security and climate change mitigation/adaptation are highlighted as the two key themes that need greater recognition. It recommended that food loss and food waste need to be defined to inform targets within the strategy. Meanwhile, establishment of a National Food Loss and Waste Baseline is recommended to quantify food loss and waste in New Zealand at the country scale and across the full food supply and consumption chain. Three actions are highlighted to reduce methane from waste: reduce waste, divert organic waste from landfill to recycling and composting, and improve and extend landfill gas capture systems.

At the farm scale, not all plant residues are collected and composted, but they may not be wasted or lost as they can be a part of regenerative growing system which could potentially improve soil health. Therefore, it is important to adopt a holistic approach to waste management in the horticulture industry. This approach should consider the entire life cycle of the fruit and vegetable production process, from the farm to the consumer, and aim to minimise waste and maximise resource efficiency. One way to achieve this is through the use of regenerative farming practices (Grelet et al. 2021), which focus on building soil health, enhancing biodiversity, and reducing the need for synthetic inputs. By incorporating plant residues back into the soil, growers can improve soil fertility and reduce the need for external fertilisers, while also sequestering carbon and reducing greenhouse gas emissions. In addition to on-farm practices, it is important to consider the entire supply chain when addressing food waste (Diaz-Ruiz et al. 2019). This includes reducing waste in processing, distribution, and retail, as well as encouraging consumers to reduce their own food waste through education and awareness campaigns.

Overall, a circular economy approach (Velasco-Muñoz et al. 2022) to waste management in the horticulture industry can help to achieve multiple benefits, including reducing greenhouse gas emissions, improving soil health, and promoting sustainable food production and consumption.

Greenhouse industries and associated environment issues

Greenhouse (covered) crop and vegetable production is an important industry for New Zealand (e.g. tomatoes, capsicums, leafy greens, herbs, strawberries, and other berryfruits). There are about 220 ha of covered/indoor crops in the North Island (mainly in Auckland and Waikato regions), and about 36 ha of covered/indoor crops in the South Island (mainly in Tasman, Marlborough, and Canterbury regions). It contributes GDP of NZ$120 million per year, and exports of NZ$35–40 million per year (HortNZ 2020). While this industry provides a significant contribution towards diversifying the New Zealand economy, it's also accompanied by a large cost (e.g. NZ$34.3 million) on energy use (e.g. electricity, coal, gas, diesel, oil, and wood pellets/biomass) for heating (HortNZ 2020), which can be a large source of particulate matter (PM)2.5 and greenhouse gas emissions.

CO_2 enrichment is commonly used in greenhouse industries in New Zealand to improve plant growth and yield, particularly during the winter months. The source of CO_2 used for enrichment in greenhouse industries in New Zealand varies and can come from a variety of sources, including by-products of other industrial processes, combustion of fossil fuels, or natural sources such as underground wells or the atmosphere, but it is important to use it in a responsible and sustainable manner to avoid contributing to climate change. In addition, aesthetics (e.g. visual environment) is also an important factor for the greenhouse industry.

Air quality associated with burning

Outdoor burning is commonly used for land management in horticultural industries. They are used for several purposes. These include orchard development, disposing of vegetation such as pruning and shelterbelt trimmings, or controlling pests and destroying diseased plant material (Baillie & Bayne 2019; HortNZ 2020). For example, because onion skins/tops cannot be returned to the field due to the risk of spreading disease, onion growers tend to burn the onion skins during the onion grading season. However, the associated smoke and odour can have adverse health and nuisance effects on people, property, and the environment (e.g. air quality) (Tasman District Council 2021). The National Environmental Standard for Air Quality, implemented by Councils, has set out a minimum amount for the purpose of health protection for PM10, carbon monoxide, nitrogen dioxide, sulphur dioxide, and ozone. The proposed PM2.5 standards are suggested to replace the PM10 standard as the primary standard for managing particulate matter (HortNZ 2020).

Regional plans include rules that manage air discharges from activities such as outdoor burning and others. For example in the Hawke's Bay**,** no burning of orchard prunings is permitted within the Napier and Hastings airshed between 1 May to 31 August, except for diseased material (Hawke's Bay Regional Council 2023). A survey undertaken with rural land managers, rural populace, and rural fire personnel within New Zealand showed that less agreement was made on that fire was a good option for use in rural land management in New Zealand because the high agreement with the construct concerning negative smoke impacts. To enable prescribed fire to continue to be a useful tool, an improved understanding of current management practices and clear guidelines around best practices in using fire in New Zealand to manage land are required, with particular emphasis on limiting smoke effects (Bayne et al. 2019). Concerns regarding fire escapes, risks to infrastructure, environmental effects, urban encroachment into rural environments and climate change may influence future use (Baillie & Bayne 2019).

Natural fertiliser management

Natural fertilisers are fertilisers made from organic materials such animal, plant, and human waste products (or by-products), that may or may not be treated by composting, fermentation, or pasteurisation. Natural fertilisers can carry chemicals and microbes that are harmful to human health. Many studies have highlighted the risk of horticultural produce such as fruits and vegetables as vehicles for transmitting microbial pathogens to humans (Sivapalasingam et al. 2004; Lynch et al. 2009). In New Zealand, Salmonella spp. and *E. coli* O157, and to a lesser extent protozoa and viruses, were the pathogens most often reported in the scientific literature as being found on produce which were caused by improperly treated manures and contaminated irrigation water (McIntyre et al. 2008). Animal wastes provide important nutrient sources for plant growth, but they also contain various human pathogens which can threaten human health through food chain (Jiang & Shepherd 2009). The prevalence of microbiological pathogens in New Zealand livestock and poultry's faeces differs with pathogen (Moriarty et al. 2011). Temperature and soil water content are the key factors affecting the survival of viruses in soil, and viruses tend to survive longer when associated with solid particles such as biosolids (MPI 2011).

Growers need to manage the risk of natural fertilisers contaminating their produce by controlling their quality, and how and when they are applied (MPI 2011). Generally, growers rely on fertiliser suppliers to control the quality of natural fertilisers. The New Zealand Standard for composts, soil conditioners and mulches (NZS 4454 2005) uses *E.coli* as an indicator for the microbiological quality of compost, but acknowledges that *E.coli* can't be related to the removal of other specific pathogens in the composting process. Composting and allowing time intervals between fertiliser application and planting can be used to reduce the risk of contamination (Warriner et al. 2009).

For better understanding the potential adverse impacts of pathogens on horticulture produce and human health by applying natural fertilisers, information on natural fertiliser types, their suppliers, application rate, timing, application method (surface or mix with soil), the time between application, and plant establishment need to be collected at a farm scale. However, this information may not be adequate to quantify the fate and impacts of pathogens from natural fertilisers, which needs further research.

Plasticulture and recycling

Plastics are used at each and every stage of the horticultural life cycle for mulching, irrigation pipes, soil solarisation, protected cultivation (e.g. greenhouse), propagation and nursery, sleeving, and packing (Patel & Tandel 2017). According to the size, plastics can be classified as macroplastics (> 5000 μm), microplastics (1–5000 μm), and nanoplastics (< 1 μm). There is increasing evidence that degraded plastics are contaminating the soil and impacting biodiversity and soil health, which can lead to reduced productivity and could threaten long-term food security (United Nations Environment Programme 2022). Plastics in soil also provides an important source of micro-and nano-plastics to waterways carried by surface runoff and erosion, and to deeper soil layers by infiltration. However, the fate of microplastics in soil is unclear (Rillig & Lehmann 2020).

A study with a loamy sand soil in Berlin, Germany, found that microplastics affected bulk density, water holding capacity, and functional relationship between microbial activity and water stable aggregates (Machado et al. 2018). Biosolids, processed from sewage sludge from wastewater treatment plants, have been identified as the biggest contributor to soil microplastics (Corradini et al. 2019). Biodegradable plastics such as biodegradable mulch, polymer encapsulated fertiliser, and polymer coated seeds have been introduced, but biodegradable polymers can still contribute microplastics to the soil (Wei et al. 2022), and biodegradable mulch can have similar environmental impacts to non-biodegradable plastics if they are left on the soil surface and transported by wind or surface runoff. So while biodegradable plastics are important for mitigating plastic pollution, the decomposition rate, the non-biodegradable components and potential adsorption of other pollutants need further investigation before it can be considered a successful non-polluting alternative to conventional plastics (Fan et al. 2022; United Nations Environment Programme 2022).

Plastic-free biosolids, improved polymers, nature-positive solutions have been proposed to address the plastics pollution issues (United Nations Environment Programme 2022). Efforts have also been made to develop systems and processes to reuse, recycle, effectively biodegrade or adequately dispose of many agricultural plastics (Figure 3) (FAO 2021). Studies on microplastics in the Southern hemisphere particularly for New Zealand and Antarctic regions are very limited (De Bhowmick et al. 2021). Future research is needed to understand the extent of plastic pollution in horticulture land uses and its impacts on soil health, biodiversity, productivity, and human health. To start with, some preliminary data such as plastic potential source, plastic type, plastic volume/weight, and its turnover can be useful to understand the potential pollution of plastics. Life cycle assessments (LCA, see details in section 2.3.3) may be used to evaluate the environmental impact of plastic over its entire life cycle, from raw material extraction to disposal. This includes considering the energy and resources used during production, use, and end-of-life disposal or recycling. Various indicators such as greenhouse gas emissions, water use, energy consumption, and land use may be used to assess the environmental impact of plastic.

Symbol	Description	Examples
	Products where the plastics become completely dispersed in the environment	• Polymer coatings of fertilizers, seeds and pesticides • Elastration bands for livestock • Dolly rope on trawl nets in capture
	Products with a high risk of dispersal into the environment or contamination that limits options for recycling	• Mulching films and irrigation tape • Plant support twines and nets • Pesticide containers and impregnated plastics • Veterinary consumables • Tree guards
	Single use products with short period of use (<6 months) but with potential for collection and some recycling	• Packaging for fertilizers and seeds • Personal protective equipment • Distribution and consumer packaging
	Single use durable products (useful life >3 years) and with potential for collection and some recycling	• Greenhouse films • Pond liners and irrigation mains • Ear tags for marking livestock • Fishing nets and cages
	Reusable products that only become waste after several use cycles and with potential for collection and recycling	• Crates for harvesting crops • Crates for small livestock • Hermetically sealed crop storage bags • Sanitizable insulated boxes for distribution of fish

Figure 3. Potential for harm to the environment and circularity of various plastic products (FAO 2021).

2.2 Risk matrix development for assessing environmental performance: Using nitrogen loss to waterways as an example

2.2.1 Review of previous methods

Nitrogen losses can be estimated with process-based models with different complexities. However, due to the complexities of the water and nitrogen processes, accurate estimation of nitrogen losses using process-based models are usually extremely difficult. In New Zealand, an issue of uncertainty/accuracy exists in terms of if Overseer's (a nutrient budgeting tool/model) outputs can be used to inform whether changes in farm management practices can lead to changes in nutrients losses from a wide variety of property types and land uses (MfE and MPI 2021).

Land managers and others are more and more interested in using index tools to conduct prompt assessment of management practices on nitrogen losses (Delgado et al. 2008). Various risk assessment tools have been developed worldwide (Delgado et al. 2006; Delgado et al. 2008; Bechmann et al. 2009; Buczko & Kuchenbuch 2010; Drewry et al. 2011; Figueroa-Viramontes et al. 2011; Delgado et al. 2013). Buczko & Kuchenbuch (2010) reviewed different nitrogen loss indicators ranging in complexity from simple proxy variables to elaborate systems of algebraic equations. These methods can be categorised into source-based, transport-based, and composite approaches. For example, a nitrogen-index tool was developed with international cooperation from many countries (USA, China, Argentina, Mexico, Canada) in spreadsheet format for prompt assessment of the effects of current and alternative management practices on nitrogen losses (Delgado et al. 2006). For this index, inputs are categorised by site, soil, crop, manure, fertiliser, irrigation, precipitation, and off-site factors, which can be completed in 5–10 min (Delgado et al. 2008). Its application indicated that this tool can be used to accurately assess the nitrate leaching and atmospheric nitrogen losses as well (Delgado et al. 2008).

Figueroa-Viramontes et al. (2011) used the Mexico Nitrogen Index to do quick evaluation of the risk of nitrogen loss for a given field under a given set of management practices in the forage systems. For this tool, inputs include information such as soil layer information, manure, fertiliser, irrigation, crop, off-site factors, water management/hydrology, and qualitative factors. The first smartphone/ tablet application (or ‘‘app’’) of the Mexico Nitrogen Index was released on 26 February 2012 to enable growers to use smartphones to conduct a nitrogen assessment on site. This app can be downloaded at no cost from the Google Play™ website (Google Play 2023) to any phones that have the Android™ system.

Bechmann et al. (2009) developed an integrated risk assessment tool, consisting of indices for erosion, phosphorus and nitrogen. Inputs for the nitrogen index include deposition, fertiliser rate, manure rate, organic nitrogen from the previous year, winter crop nitrogen, and tillage nitrogen (Bechmann et al. 2009). Integrated index is calculated as the average of nitrogen and phosphorus indices, and integrated index is ranked low, medium, high, and very high.

While most index tools need many amounts of inputs, some simpler indices have been proposed. For example, McDowell et al. (2002) developed a nitrogen-indexing system where nitrogen transport characteristics (texture and permeability) and nitrogen source characteristics (fertiliser and manure application method and timing) are considered. Each factor is assigned a score, then the products of four factors will be estimated to be the nitrogen risk.

In New Zealand, the Tiaki programme nitrogen-risk scorecard was developed by Fonterra (Fonterra 2023). The scorecard was developed for dairy farmers to assess potential nitrogen loss risk of their dairy farms and identify appropriate management practices to reduce their environmental impact (MfE and MPI 2021). In this scorecard system, management practices including nitrogen fertiliser application, stock management, imported feed, irrigation, cropping and cultivation, and effluent management are assessed. Each management practice starts from a position of zero points, with points being added under each key risk practice. Then scores for each practice area are summed up. All scores less than 20 are considered very low risk, and all scores greater than 80 are considered high risk. While this kind of scorecard system is easy to use, the scoring may need to be changed depending on the contexts (e.g. soil type). For example, the nitrogen-risk scorecard assumes that more intensive cultivation had more risk of nitrogen loss, which may not be true. Previous meta-analyses in arable cropping indicated that, on average, no tillage, compared with intensive tillage, increased the risk of both nitrate leaching and N_2O emissions globally (van Kessel et al. 2013; Daryanto et al. 2017; Li et al. 2023).

2.2.2 Thoughts on development of a risk matrix of nitrogen loss

It seems there are no risk matrix methods developed specifically for horticulture land use in both New Zealand and worldwide. Risk assessment is defined as "a process intended to calculate or estimate the risk to a given target organism, system or sub (population), including the identification of attendant uncertainties, following exposure to a particular agent, taking into account the inherent characteristics of the agent of concern as well as the characteristics of the specific target system" (OECD 2003). According to this definition, assessing the risk of nitrogen loss should be made by accounting for two components: “system” (e.g. a combination of soil (e.g. drainage) and topography (e.g. slope)) and “exposure” (e.g. pressures imposed by management practices and weather/climates (e.g. rainfall)). Therefore, both components should be considered when developing a risk matrix.

To identify the key management practices that affect the risk of nitrogen loss would be crucial. The key management practices in horticulture land uses that are responsible for nitrogen losses may be different to other land uses (e.g. dairy). Therefore, development of a risk matrix method for evaluating nitrogen loss to waterways across all horticultural land uses is needed. In horticulture, the main management practices that affect the risk of nitrogen loss to waterways may include but not exclusively nitrogen fertiliser use and rates, crop type, cultivation, irrigation, fallow, rotations, and compaction. For each factor (including management practices, soil, topography, and weather/climates), a risk score can be expressed either in a discrete/categorical or continuous manner based on the real data. The risk score and weighting of each factor can be determined using existing knowledge (e.g. expert knowledge or literature findings). Alternatively, the risk score and weighting of each factor can be determined based on process-based modelling (e.g. Agricultural Production Systems sIMulator (APSIM)) under different scenarios (e.g. various combinations of different degrees of factors). By using comprehensive modelling exercises, the potential interactions between factors, which are usually ignored in previous risk matrix method, can also be considered. Based on the risk score, and their weighting, the degree of mitigation required can be determined correspondingly. The higher risk score, and higher weight, the higher the degree of mitigation that is required.

Table 8 shows an example of what a risk matrix for nitrogen loss may look like based on a discrete risk scoring system (Question marks are shown where the exact classification and threshold need to be determined from further research). For example, nitrogen fertiliser may have high weighting in determining nitrogen loss, if the fertiliser application rate is very high, then a high degree of mitigation (reducing nitrogen fertiliser) is required. If the risk score is high, but the weight is low, a high degree of mitigation may not be necessary. For example, inversion tillage has the highest degree of damage to soils which may make soils more vulnerable to nitrogen runoff loss. However, it may not be important (i.e. low weighting) for nitrogen loss from an orchard in flat areas. In this case, inversion tillage between tree rows for the purpose of weed management may not be harmful. In such cases, low degree of mitigation in terms of tillage is required.

Table 8. An example of a risk matrix for nitrogen (N) loss to waterways[1].

Assessment components	Factor	Risk description	Farm data	Weighting score	Risk score	Degree of mitigation required
System	Soil (e.g. drainage)	**?**	?	?	?	?
	Topography (e.g. slope)	**?**	?	?	?	?
Exposure	N fertiliser	**More N input, higher risk** 0-100 kg N/ha, low 100-150 kg N/ha, medium 1000-200 kg N/ha, medium, >200 kg N/ha, high >150 kg N/ha, high	180 kg N/ha	High	High	High
	Cultivation	**More intensive tillage, higher risk** No-tillage, low non-inversion tillage, medium inversion tillage, high	inversion tillage	Low	High	Low
	Compaction	**More compaction, higher risk** no to low compaction (BD>1.2 g cm^{-3}), low medium compaction (1.6>BD>1.2 g cm^{-3}), medium high compaction (BD>1.6 g cm^{-3}), high	1.1 g cm^{-3}	Medium	Low	Low
	Irrigation	**More irrigation, higher risk**	?	?	?	?
	Fallow	**Longer fallow, higher risk**…	?	?	?	?
	Rainfall	**Higher rainfall, higher risk**	?	?	?	?

[1] Question marks are included where the exact classification and thresholds need to be determined from further research.

Table 8 gives an example of how to determine the risk score and weighting score for each factor from each component, and how we can use this information for guiding the mitigation. However, if we want to compare the total risk of nitrogen loss to waterways between different cropping systems or within the same crop system but with different practices, we may be interested in calculating the total risk score, as proposed by others (McDowell et al., 2002; MfE and MPI, 2021). This approach allows for a comprehensive comparison of the overall risk levels and can help identify areas where further mitigation efforts may be needed. The key is to understand if the contributions from different factors within/between components are additive (+) or multiplicative (x). For example, the contributions from irrigation and rainfall may be additive, while the contributions from nitrogen fertiliser and the system (soil and topography) may be multiplicative. Similarly, the relationships of contributions from different factors can be determined by existing knowledge or scenario modelling.

Nitrogen is lost to waterways through leaching and surface runoff. Trade-offs can exist between leaching and surface runoff, but leaching loss and surface runoff loss may have different effects on the ecosystem and on human wellbeing. Risk of nitrogen leaching loss may be different to risk of nitrogen runoff loss. For example, flat areas have a higher risk of leaching, while sloping areas have a higher risk of surface runoff loss. While leaching is more likely to contaminate groundwater, which is the main source of drinking water, runoff loss is more likely to contaminate surface water which is used for agricultural purposes such as irrigation and livestock in New Zealand. In this scenario it would be good to combine the two mechanisms of nitrogen loss if the aim is to assess the risk of total nitrogen loss. However, if the aim is to assess the risk of impact, then it's worth separating them during the risk assessment.

2.3 Key performance indicators (KPIs) to assess environmental performance

2.3.1 Resource use indicators

Water use

Crop water use efficiency (WUE) can be defined as the ratio of crop yield to water use (i.e. kg of crop produced or harvested to m^3 of water evapotranspired by the crop) (Fernández et al. 2020). Water use efficiency has received more attention in water stressed environments, and where irrigation is usually required, such as northwest of China. In this regard, irrigation water use efficiency (IWUE) or water productivity (WPI), defined as the ratio of yield to irrigation amount (i.e. crop yield in kg per m^3 of water applied as irrigation), is also used to assess WUE of various irrigation methods (Cai et al. 2021). For example, lower IWUE values were obtained under subsurface drip and furrow irrigation systems compared with sprinkler irrigation in onions field grown in the Mesilla Valley of southern New Mexico (Al-Jamal et al. 2001). This was due to excessive irrigation under subsurface drip and higher evaporation rates from fields using furrow irrigation (Al-Jamal et al. 2001). In apple orchards on the Chinese Loess Plateau, subsurface irrigation with ceramic emitters buried at 40 cm depth had greater IWUE than subsurface drip irrigation. However, the relative IWUE is also related to the irrigation amount. For example, in a grain sorghum field with a fine textured soil in the southern High Plains, IWUE of subsurface drip irrigation was greater than spray irrigation and low energy precision application irrigation at deficit irrigation at 25% and 50% of full irrigation, while IWUE of spray irrigation was greater than the other two at deficit irrigation at 75% and full irrigation point (Schneider & Howell 1998). At a more microscopic scale, instantaneous water use efficiency was also calculated as the ratio of photosynthetic assimilation to transpiration from short-term gas exchange measurements.

The WUE indicator can be used to guide practices for more sustainable water use. It is relatively easy to measure, understand and communicate. However, it is worth adding a cautionary note about the use of the term water-use efficiency. It is critical that the terminology around water-usage is unambiguous, as there is a degree of confusion and obfuscation in the literature. First, only water quantity is considered in the WUE, the water scarcity and its temporal distribution/allocation and hence potential environmental impacts (e.g. lower water rates resulting from water abstraction can contribute to higher concentrations of natural and human pollutants; water scarcity can threaten vegetation growth hence ecological stability) are ignored in WUE. For example, under the same WUE, the adverse effects of water use on the ecosystem may be greater in a more water limited environment, both in a spatial and temporal domain. Therefore, water scarcity in both spatial and temporal domain need to be considered for better assessing efficiency of water use, especially from irrigation. In addition, it’s not suitable to compare WUE for different crops as their yields are not comparable. In this regard, both water footprint and nutrient density of crops were compared for food system sustainability (Sokolow et al. 2019). Water use efficiencies between different crops were compared as micronutrient outputs per litre overall net water use (green and blue water) and water use per weight of protein (Damerau et al. 2019). A stronger reliance on more nutrient-dense foods was found to result in higher water-use efficiencies (Damerau et al. 2019). Fernández et al. (2020) noted that a limitation of WPI, is that it does not take rainfall into account. The crop water-use efficiency and water productivity should be used to give an indication of the value of irrigation, along with the trade-offs and impacts. This would allow us to identify the water savings that might be achieved through good irrigation management, and the impact these could have on water resources.

The KPIs of water use efficiency and irrigation water use efficiency or water productivity also need to be linked to the larger hydrological context. In terms of water security, Grafton et al. (2018) asserted that increasing irrigation water-use efficiency has rarely delivered the presumed public-good benefits of increased water availability. They reasoned that in order to improve local water security and reduce water scarcity that any consideration of water-use efficiency must be accompanied by robust and full water-accounting through understanding water inflows, storages, and outflows in the catchment, plus an evaluation of trade-offs and impacts through consideration of efficiency, productivity and the required environmental flows.

Nutrient use

Nutrient use efficiency is used to differentiate plant species, genotypes, and cultivars for their ability to absorb and utilise nutrients for maximum yields. It is usually based on (a) uptake efficiency, (b) incorporation efficiency, and (c) utilisation efficiency (Baligar et al. 2001). Various indices are developed. These include nutrient efficiency ratio, physiological efficiency, agronomic efficiency, agro-physiological efficiency, and apparent nutrient recovery efficiency (Baligar et al. 2001). Depending on the indices used, yield, nutrient uptake, nutrient amount applied as fertiliser and nutrient baseline in non-fertilised treatments are usually included to characterise nutrient use efficiency.

Among nutrient use efficiency indices, nitrogen use efficiency (NUE) is the most widely investigated. For example, leaf NUE (an indicator of nutrient efficiency ratio), measured as the leaf dry weight produced per unit of nitrogen in the leaf, was used to indicate whether nitrogen is being used efficiently to produce dry matter in a tree (Choi & Rom 2011). Nutrient use efficiency can be used to reflect not only the ability of plants to uptake, incorporate and utilise nutrients, but also the risk of nutrient surplus and subsequent loss to the environment. A study from the Sustainable Vegetable Systems project carried out by PFR indicated that optimum nitrogen treatment of 200 kg N/ha applied to a potato crop resulted in nitrate leaching of 21 kg N/ha, which was only slightly higher (only by 6 kg N/ha) than nitrate leaching (~15 kg N/ha leached) when no nitrogen was applied (Searle et al. 2022).

Their study implied that the appropriate use of fertiliser in terms of rates and application times can be achieved to increase crop yield, while minimising nitrogen leaching. High nutrient use efficiency is expected as this usually implies maximum productivity with minimum nutrient inputs. However, very low nutrient input can produce high nutrient use efficiency but not necessarily high production, which may not be economically sustainable.

Nutrient use efficiency was also widely investigated for various crops with different variables, such as N fertiliser application rate on NUE of forage kale crops (Chakwizira et al. 2015), management practices on NUE of pasture systems (Li & Snow 2010), water and nitrogen limitation on NUE of maize crops (Teixeira et al. 2014). However, relatively less research has been carried out on the nutrient use efficiencies in horticultural sectors in both New Zealand and overseas. Nutrient use efficiency usually focuses on a single nutrient element, which cannot capture the full picture of nutrient use and contamination. In addition, nutrient use efficiency is not directly related to the amount of nutrient losses and the potential damage to the environment.

Energy use

The energy equivalent of inputs and output are used to estimate the energy values (Canakci & Akinci 2006; Rafiee et al. 2010). The input energy in agricultural systems can be divided into direct (e.g. human labour, diesel fuel, electricity and water for irrigation) and indirect (e.g. farmyard manure, chemical fertiliser, chemicals and machinery) or renewable (e.g. human labour, farmyard manure and water for irrigation) and non-renewable (e.g. electricity, machinery, diesel fuel, chemicals, and chemical fertilisers) forms. The energy output usually represents agricultural product (e.g. fruit yield) or its energy equivalent. Energy use efficiency, calculated as the ratio of energy output to energy input, is widely used to assess the energy values in agricultural systems. It is also called energy input-output ratio or benefit to cost ratio. In addition, energy productivity (e.g. product output/energy input), specific energy (e.g. energy input/product output) and net energy (e.g. energy output-energy input) were also reported.

Energy use efficiency and other energy value indices can be used to reflect not only the efficiency of energy use, but also the risk of potential environmental issues (e.g. greenhouse gas emissions) based on the assumption that efficient use of energy is accompanied with minimised environmental problems. Therefore, a unit of energy output requires less energy input and causes less environmental issues in agriculture systems with higher energy use efficiency or energy productivity. However, the potential adverse impacts on environment per unit of energy input may be associated with the energy sources. In addition, energy use may not fully capture the environmental impacts, for example, machinery use not only increases greenhouse gas emissions by energy consumption, but also increases soil compaction risk which further adversely affects a wide range of environmental performance (Hu et al. 2021).

2.3.2 Environmental footprint

Water footprint

Water footprint (WF) was introduced by Hoekstra & Chung (2002) as an “indicator of water use behind all the goods and services consumed by one individual or the individuals of a country”. According to the WFN (water footprint network), Water Footprint Assessment (WFA) comprises three segments: the “green water footprint” measures the rainwater that is evapo-transpired or incorporated by plants; “blue water footprint” measures the surface- or groundwater withdrawn from a water body; “grey water footprint” measures a hypothetical amount of water necessary for assimilation of discharged pollution

(Hoekstra et al. 2011). A full WFA should comprise four stages: setting goals and scope of the analysis, WF accounting, sustainability assessment, and response formulation (Hoekstra et al. 2011). The WFA method aims to provide useful insights mainly from the water resource management perspective (Boulay et al. 2013). Because water use impact is related to local and temporal water availability, water scarcity footprint has been proposed to compare volumetric water footprint with local scarcity factors (Boulay et al. 2018). The need for a consensus methodology precipitated in the establishment of the WULCA (Water Use in LCA) working group (Boulay et al. 2015), resulting in the development of the AWARE (available water remaining) methodology (Boulay et al. 2018). While WFA accounts the total green water used, some LCA practitioners argue that only net green water (the difference between e.g. a cropland and natural vegetation) should be accounted (Quinteiro et al. 2015). While WFA usually leads to a standalone indicator, WF in LCA is regularly reported among a set of other impact categories (Pfister et al. 2017). The WFA method can be used to quantify the impacts of goods and services on freshwater scarcity and quality (Clothier et al. 2012). However, a bigger volumetric footprint does not necessarily mean a bigger environmental problem, which may be avoided in the LCA WF. Disputes around water footprint always exist between WFA and LCA WF communities, for this reason, Lathuillière et al. (2018) proposed a harmonisation/merge of the two methodological approaches. In addition, WF has been criticised for conflating different types of impacts when it sums rainwater, pumped irrigation water, and hypothetical volumes of polluted water into one number (Einarsson & Cederberg 2019).

In New Zealand, WFs of apple production in three regions (i.e. Hawke's Bay, Tasman, and Central Otago regions) were assessed using four methods: the consumptive approach of the WFA, two approaches in LCA framework and the hydrological approach. The hydrological approach goes beyond considering water consumption alone and takes into account the net change in water resulting from all hydrological flows within the system (Deurer et al. 2011).The consumptive method showed that water use (green + blue water) was 23 L/apple, being much less that the figures from WFA (106 L/apple) and FAO (70 L/apple). While it's advocated to assess WF in LCA, Clothier et al. (2012) found that the two LCA-based water footprint methods were quite insensitive to local conditions, and did not help to improve the performance of individual growers. In addition, hydrological approach produced much lower total WF than the consumptive method (-5.3 vs 136.5 L/kg), and the use of the hydrological method was advocated because it correctly represents the flows and storages of water, and the blue water footprint can be directly linked to the hydrological impact of groundwater recharge. The hydrological method was used to assess water use through the life cycle of grape-wine production in Marlborough and Gisborne regions, and the results indicated a large variability of blue WF even within a region and the impacts of the winery phase on water use were very small compared with that of the vineyard (Herath et al. 2013). This method, in combination with modelling, was also used to quantify the water footprint of rain-fed potato production in the Manawatu region (Herath et al. 2014).

Carbon footprint

There is a wide spectrum of definitions used for the carbon footprint (CF) (Alvarez et al. 2016). On one side, there is the land-based CF definition developed in the context of ecological footprint (Rees & Wackernagel 1996) as presented in the previous section, i.e. a forest land needed to sequester CO_2 emissions (Mancini et al. 2016), also called "energy footprint" (Fang & Heijungs 2015). On the other hand, there is the CF seen as an LCA limited to just the climate change impact category (Laurent et al. 2012). There are, generally, two approaches to CF calculation: LCA and Input-Output analysis, but also their modifications and hybridisations (Giama & Papadopoulos 2018).

The CF is often also called GHG footprint (Čuček et al. 2015) to assess the climate change impact while all GHGs emissions were converted to CO_2 equivalent (CO_2-eq) accounting for the differences in global warming potential (GWP) between the different gases, relative to the global warming effect of CO_2. This has typically been considered for warming over a 100-year period; sometimes referred to as GWP_{100}. As more information has become available, warming potential values have been modified; for example, the GWP_{100} for N_2O has reduced by 11% from 298 to 265 (IPCC 2014), although this has not been implemented in NZ's GHG inventory (MfE 2022b). Furthermore, the longevity of the gases in the atmosphere can be considered by separating the so-called long-lived greenhouse gases (CO_2 and N_2O) from CH_4 which has a shorter half-life (i.e. short-lived gas). Separating out CH_4 from CO_2 and N_2O would be consistent with NZ commitments that specifically target animal CH_4 emission reductions by 2030 and 2050[2] .

The IPCC 2006 Guidelines (Eggleston et al. 2006) for National Greenhouse Gas Inventories recommend a production-based accounting method in which emissions are calculated by multiplying activity data by an emissions factor. However, different emission factors are usually used in different methodologies based on different assumptions (Hawkins et al. 2016). Emission factors and activity data sources used in the national inventory, and best suited to New Zealand conditions, are published by MfE (MfE 2022a) and MPI (MPI 2022). These are updated frequently as new or improved methods, activity data and emission factors for estimation become available. Studies on footprints for New Zealand farms and orchards should normally use these methods and factors. This may be an issue for comparison with overseas studies where different emission factors or activity data may be used. Similarly, where emission factors or methods have been revised then these should be accounted for when making comparison to historical estimates that were based on previous methods and or emission factors. For example, the N_2O GWP_{100} was revised down by 11% between the IPCC Fourth and Fifth Assessment Reports of the IPCC (IPCC 2014). Some methodologies, e.g. the New Zealand GHG inventory, still use the earlier value.

In New Zealand, Hume et al. (2009) collected resource and energy data by 59 face-to-face surveys with apple orchardists from Hawke's Bay, Nelson and Otago. With those data, CF (CO_2-eq) was calculated for both production and post-orchard stages using LCA and Publicly Available Specification (PAS 2050) for GHG emission. In that study, two approaches to GHG foot printing have been used to inform the discussion: product-focused LCA (based on ISO 14040 and 14044) and the PAS 2050. The objective was to establish the "hotspots" for carbon emissions within the apple supply chain. They found that the main life cycle stages contributing to total emissions in the supply chain of apples are shipping, consumer, retailer, and repacking. The New Zealand orchard, packhouse and port life-cycle stages contribute 10% and 13% to overall GHG emissions for 'Braeburn' and 'Royal Gala' apple varieties respectively, and the corresponding contributions for organic apples were 15% ('Braeburn') and 17% ('Royal Gala') respectively. Gentile et al. (2014b) highlighted the importance of soil carbon stock for assessing carbon footprint of New Zealand kiwifruit, which is usually not considered owing to the lack of data. Page (2011) calculated CF of organic kiwifruit and apple production systems in New Zealand using the LCA method and found that the studied systems had a net sequestration from 2.4 to 5.0 tons CO_2-eq/ha/year and therefore can be potentially considered as carbon sinks under the Kyoto Protocol.

Saunders & Barber (2008) compared New Zealand production (dairy products, lamb, apples, onions) shipped to the UK with a UK source using the CF and food miles approaches. They argued that climate change should be addressed through a trade policy focus on the more comprehensive task of reducing carbon footprints over time, rather than a narrower focus on carbon miles. As discussed in

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https://www.hbrc.govt.nz/assets/Document-Library/Information-Sheets/Air/Burning-Info-Sheet-Horticulture.pdf
blic/2019/0061/latest/LMS183736.html"Climate Change Response (Zero Carbon) Amendment Act 2019 No 61, Public Act Contents – New Zealand Legislation

Section 2.1.5, from 2008–2010, various MPI-funded projects used LCA to measure emissions from horticulture production systems including kiwifruit, wine, apples, and berry fruit. In 2021, updated LCA protocols for apples, kiwifruit, and wine were reported to MPI (McLaren et al. 2021), showing a 13% reduction in LCA footprint for NZ apple exports and a 24% reduction for kiwifruit delivered to a German retailer between 2008–19.

The use of greenhouse gas footprints can serve as eco-credentials in the market-place to enable achievement of eco-premium prices (Clothier 2015; McLaren et al. 2017). There is ‘virtuous circle’ linking sustainable practices, eco-credentialling, and premium product-placement and pricing. Most of the data required for such credentialling can be collected in a reasonably straight-forward manner, either by the grower, or consultants. An exemplar of this is the certification by the viticultural industry is called Sustainable Winegrowing New Zealand (New Zealand Wine 2023). It was the first to be established in the international wine industry in 1995 and currently ~86% of the vineyard producing area in New Zealand is SWNZ certified, and over 90% of the wine produced is processed in SWNZ certified facilities. Essentially, SWNZ is business-as-usual reporting for the New Zealand viticultural industry, with SWNZ certification covering climate-change, water, waste, plant-protection, people, and soil.

Simpler approaches have been used for within-farm or within-orchard carbon footprints of biogenic GHG emissions using IPCC protocols (Commission 2018), rather than full LCA determinations of the carbon footprint for the whole supply chain from orchard through overseas supermarket to consumer (Hume et al. 2009). Recently PFR produced estimates of greenhouse gas emissions for nominal arable and vegetable rotations for the Foundation for Arable Research and Horticulture New Zealand (McNally et al. 2021a; McNally et al. 2021b). These studies followed the methodologies used in the national inventory using activity data and emission factors (MfE 2020b; MPI 2022). The emissions were those that occurred on the farm or orchard only, not the emissions that occurred offsite, such as emissions from the manufacture of fertiliser are not included. Activity data were collected through surveys of growers and provided by FAR and Horticulture New Zealand. Data included CO_2 emissions from lime, fuel and electricity in addition to N_2O and CH_4 emissions from fertiliser, residues and animal grazing. They did not include emissions associated with activities outside the farm boundaries. A similar approach was used to estimate emissions from walnut orchards in Canterbury (Thomas & McNally 2022).

Nitrogen footprint

Nitrogen (N) footprint has been defined by Leach et al. (2012) as the total amount of reactive nitrogen (Nr) released to the environment. There are several approaches and methods, depending on the perspective (Einarsson & Cederberg 2019): the total Nr caused by consumption mainly considering diet (Leach et al. 2012; Martinez et al. 2019); total nitrogen losses to the environment per unit of product (Leip et al. 2014), nitrogen use efficiency (Erisman et al. 2018) or the nitrogen pollution embedded in international trade (Oita et al. 2016). In several studies, the nitrogen footprint also includes emissions of N_2, which does not contribute to any environmental pressure and does not depend on a scarce resource (Peñuelas et al. 2013), but gives a measure for the anthropogenic mobilisation of nitrogen (Pelletier & Leip 2014). Nitrogen demand has also been accounted together with phosphorus as the nutrient footprint (Grönman et al. 2016). Einarsson & Cederberg (2019) critically assessed models and proposed uses for the nitrogen footprint and explored options for further development. They found that nitrogen footprint models vary widely in approach, system boundaries, scope of activities, data requirements, disaggregation rate, assumption, and results. As Einarsson & Cederberg (2019) advocated, “N footprint merely quantifies gross N emissions irrespective of time, location, and chemical form, it is a crude proxy of environmental and health impacts". However, they also argued that "the N footprint in its present form is already fit for some purposes, and therefore further development towards impact assessment may be unnecessary or even undesirable" because this may bring more uncertainty, more complexity, and more work. SPASMO, APSIM, and Overseer are models that can forecast Nr, and in turn, estimate the nitrogen footprint of horticultural land uses. To our best knowledge, the concept of nitrogen footprint has not been introduced for horticulture in New Zealand, but has been introduced to compare different dairy farm systems in China and New Zealand (Ledgard et al. 2019). In this study (Ledgard et al. 2019), the nitrogen footprint was calculated as the total emissions of reactive nitrogen (including NO_3^-, NH_3, N_2O and NOx) per kg of milk for cradle-to-farm-gate. They found that the nitrogen footprint was 1.3–2.3 times higher for the housed-cow Chinese farm systems than the year-round pasture-grazing New Zealand farm systems (Ledgard et al. 2019).

Biodiversity footprint

Biodiversity is a broad concept that encompasses all biotic variation, from genes to ecosystems, so attempting to reduce what is essentially a multidimensional concept to a single unit is not possible (Whittaker 1972; Magurran 1988; Purvis & Hector 2000). Measurements of diversity at one place, one time or one group is uninformative, whereas comparable measurements from multiple places, time or groups can address crucial questions related to how diversity arose and how we can maintain, or even enhance it (Purvis & Hector 2000). However, 'indicators' or measures for biodiversity, their application, and procedures for monitoring their trends is lacking (Stirn & Oldeland 2018).

To determine the effect of land management/land use on biodiversity; the diversity of biological organisms in that system need to be quantified. Birds have been widely used for this purpose (FAO 2019b). However, by the time people measure a decline in populations of birds to respond to changes it may be too late to reverse their decline. The time it takes for a noticeable increase in bird populations could make it difficult to identify which management changes led to the increase.

Re-establishment and maintenance of existing indigenous plant species in farmland is an important first step and needs to be incorporated in any future biodiversity KPIs. Also, to the invertebrates that will colonise these plantings, and in the longer term, the vertebrate species that will use these habitats. However, it is still uncertain how much such re-established habitats will contribute to conservation of protected or endangered species.

To determine what the appropriate metrics for biodiversity could be, we need to understand what information we want to obtain from the KPI. For example, food producers may want to know whether a land management practice is having a positive or negative impact on biodiversity (assuming it is not the practice of clearing existing natural vegetation). This could in turn inform consumers as to how the production of a food item may impact on biodiversity. Alternatively, consumers may want to know that the food they are purchasing has not adversely impacted the country of origin's conservation of wild species (Figure 4).

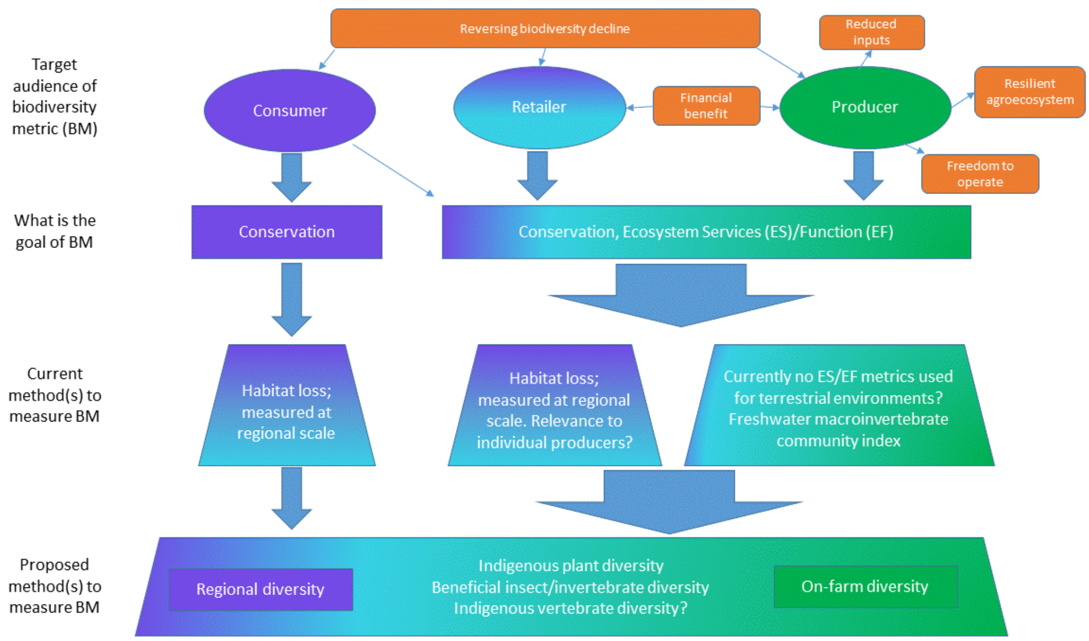

Figure 4. The potential target audience, putative aim and methods of biodiversity key performance indicators (KPIs). The boxes in orange highlight potential outcomes that could be achieved through adjusting food production practices based on biodiversity outputs. The proposed method for retailers/producers could use KPIs based on plants and invertebrates; plants can be manipulated (e.g. ecological restoration) to increase biodiversity, invertebrates display species-specific responses rapidly to changes in management, providing a measure of impact. Vertebrate biodiversity KPIs may be used for measuring longer term impacts (>10 years) (From Hu et al. (2022)).

To gauge the value of such an approach a case study explored the feasibility of using ecological models for applying an ecosystem services-based approach to environmental risk assessment (Van den Brink et al. 2021). Four ecosystem services were included in this case study; soil quality regulation, pest control, pollination, and recreation. For the soil quality regulation ecosystem service, springtails and earthworms were the service providing units, for the pest control ecosystem service it was ladybirds, for the pollination ecosystem service it was honey bees and for the recreation/cultural ecosystem service it was the meadow brown butterfly. A broad-spectrum organophosphate insecticide was used as the case study chemical. The study demonstrated that the insecticide posed an unacceptable risk to natural pest control from a non-target arthropods, pollinators, and culturally important arthropods, such as butterflies. The study showed this ecosystem services-based approach could allow for determining the acceptability of a management tool on the modelled and extrapolated effects on the service providing units.

A biodiversity footprint has been proposed to assess biodiversity as affected by land use. Biodiversity is usually linked with consumption (Lenzen et al. 2012) or a product based on LCA framework (Asselin et al. 2020). As an example, a proposed metric has attempted to integrate biodiversity in life cycle assessments by measuring biodiversity loss as land use per kg product plus potential biodiversity loss from land use (referred to as the “potentially disappeared fraction”) (Chaudhary & Brooks 2018). The metric uses country average characterisation plus reliable certification schemes for organic production (which are considered to be associated with higher biodiversity). A country’s characterisation factor relates to the country’s land use that could cause biodiversity damage (potential species lost per m^2) for mammals, birds, amphibians, reptiles, and plants. Using defined land use types (e.g. annual crops, permanent crops, pasture, intensive forestry, extensive forestry, and urban land), it attempts to calculate such characterisation factors using the species-area relationship (SAR) model multiplied by a vulnerability score assigned to a species group (Chaudhary et al. 2015). This approach takes such a high-degree view of biodiversity that it may result in overemphasising the contribution of a country or a system of food production to declining biodiversity. Conversely such a metric could overestimate the country or food system's contribution in increasing biodiversity. It does not consider that some primary production systems (e.g. Integrated Fruit Production in New Zealand apples) can result in similar rates of invertebrate biodiversity as organic production systems (Malone et al. 2017). Nor does it acknowledge conservation or ecological restoration efforts within a country. It also does not inform growers as to how their management practices may be impacting biodiversity on their farm and surrounding environment. Given the multiple dimensions and complexities of biodiversity, it was proposed that a range of units will be needed for a comprehensive picture of how consumption drives biodiversity loss (Marques et al. 2017).

Other footprints

Ecological footprint

The ecological footprint is defined as "the aggregate area of land and water in various ecological categories that is claimed by participants in that economy to produce all resources they consume, and to absorb all their wastes they generate on a continuous basis, using prevailing technology" (Wackernagel & Rees 1997). Today's ecological footprint, as used by Global Footprint Network, GFN, (Footprintnetwork org 2020), accounts human use of cropland, forests for timber, built-up land, grazing land, and fishing grounds on the consumption side, and a land needed to capture carbon dioxide on the waste absorption side (Lin et al. 2018). Another essential part of ecological footprint accounting is quantification of biocapacity, as the amount of biological productivity available to provide the resources and waste absorption. Both the footprint and the biocapacity are expressed in "global hectares," which is a hypothetical hectare of global average productivity. The ecological footprint measures how fast we consume resources and generate waste compared with how fast nature can absorb our waste and generate new resources.

Another popular GFN output with a wide media appeal (overshootday.org/ newsroom) is the Earth Overshoot Day - "the date when humanity's demand for ecological resources and services in a given year exceeds what earth can regenerate in that year" (overshootday.org). It was found that humanity was overshooting the planet's regenerative capacity by 61–146% in 2010 (Mancini et al. 2016). Although the ecological footprint has been widely used, it fails to capture many of the important human pressures on the earth systems. As Van Den Bergh & Grazi (2015) advocated: "It would be good to state this clearly that ecological footprint is an incomplete indicator of environmental impacts in all footprint publications, because most innocent users, understandably, interpret the ecological footprint as an overall environmental or (un)sustainability indicator." While the ecological footprint can be useful to quantify the consumption-absorption balance at large scales, it has rarely been used to characterise environmental effects at the orchard or farm scale.

Land footprint

Land footprint is used to uncover the connection between land use and destination of final consumption, such as for the European Union (Steen-Olsen et al. 2012) and for the entire globalised economy (Yu et al. 2013). It measures the amount of land required for the supply of food, materials, energy, and infrastructure. Land use can be indicated either by yield (expressed in global hectares, as in the ecological footprint) (Weinzettel et al. 2013) or, for example, by net primary productivity appropriation (Weinzettel et al. 2019). The appropriated area of land can provide important insights – for example on how consumption in developed countries drives the land use in developing countries (O'Brien et al. 2015) or on the limits of bio-economy (Liobikiene et al. 2020). But the land-use effect on the environment is by no means clear and linear, since the soil and climate characteristics largely differ, as well as land-use type and intensity (Schaffartzik et al. 2015). Therefore, contradictory results can be obtained from different calculation methods. It seems to be more suitable at large scales (e.g. national, regional or global) but not at the farm or orchard scale.

Chemical footprint

Chemical footprint accounts for all chemical substances released into the environment which may ultimately lead to ecotoxicity and human toxicity impacts (Hitchcock et al. 2012; Sala & Goralczyk 2013). A list of chemical substances is exhaustive, including pesticides or heavy metals. The research on chemical footprint in an agricultural area is quite limited, and there are no mature approaches for calculating chemical footprints as in the case of other members of the footprint family. Sala & Goralczyk (2013) proposed at least two different approaches and steps to calculate a chemical footprint, applicable at the micro- as well as at the meso- and macro-scale. The first step (step 1) is related to the amount of chemicals used and emissions along the life cycle of a product, sector, or entire economy, to assess potential effects on ecosystems and human health. The second step (step 2) aims to assess to what extent actual emissions of chemicals harm the ecosystems above their capability to recover (carrying capacity of the system). Soheilifard et al. (2020) used the chemical footprint concept to investigate pesticides' toxicological effects in citrus orchards, located in the Safi Abad region, Khuzestan, Iran, by determining the proportion of pesticides in different areas (air, soil, and canopy), which facilitates toxicity assessments of pesticides in citrus orchards.

Material footprint

Material footprint is usually used to uncover the global patterns of material extraction and use embedded in international trade and consumption (Giljum et al. 2015). It shows how the post-industrial economies achieved decoupling of economic growth from material consumption mainly by externalisation to developing countries (Wiedmann et al. 2015). The material footprint does not reflect scarcity of the material. For this reason, the resource depletion footprint, where material footprint is weighted by respective depletion potentials, was proposed by Fang & Heijungs (2014). Although material consumption is associated with environmental impact, no direct relationships can be developed as the environmental impact is related to the specific material and its origin as well. Similar to land footprint, material footprint is mainly used to provide a consumption perspective of resource use and new insights into the actual resource productivity at large scales (e.g. national or global) (Wiedmann et al. 2015). Material footprint has not been used at the farm/orchard scale, where material use was usually converted to GHGs emissions-based C footprint (Hume et al. 2009; Yan et al. 2016). There is a need to conduct research to understand the distribution of all types of materials used on the horticulture land, and to identify alternative or longer-lived materials regarding non-organic waste, such as black ground cover plastics, plastic growing pots, and shade and shelter cloth to reduce the material footprint (HortNZ 2021).

Phosphorus footprint

The concept of phosphorus footprint was first used by Wang et al. (2011) to measure phosphorus demand of China's food chain. It was also used to measure the use of phosphorus as a resource and phosphorus losses to water bodies at large scales (e.g. national) (Obersteiner et al. 2013; Van Dijk et al. 2016; Zhang et al. 2017). On the other hand, Grönman et al. (2016) developed a framework to calculate both nitrogen and phosphorus footprints (called nutrient footprint for the combination) from the aspects of nutrient use efficiency and nutrient intake for individual crops from a life cycle perspective. The phosphorus footprint was explicitly defined as “the total P demand as a result of population’s consumption” by Jiang et al. (2019). It can be expressed either in total units of phosphorus or in unit of phosphorus per capita. As yet, research on the phosphorus footprint is very limited, mainly focusing on agriculture and food. For example, Huang et al. (2019) assessed the phosphorus footprint of the Chinese city of Zhangzhou, MacDonald et al. (2012) assessed the phosphorus footprint embodied in the agriculture of the United States, and Metson et al. (2012) analysed the impact of diet on phosphorus demand. It has not been used in horticulture for improving phosphorus use efficiency and minimising its losses.

Energy or energy footprint

The energy footprint is both expressed as the carbon component (e.g. CO_2 emissions (Daccache et al. 2014) or land area required to absorb CO_2 emissions (Banerjee et al. 2021)) of the ecological footprint (Wiedmann 2009; Mancini et al. 2016) or the amount of energy consumed along the supply chain (Onat et al. 2015). For example, CO_2 emissions from irrigation were calculated based on the energy needed for abstraction (pumping) and water application (Daccache et al. 2014). The energy footprint relates to the latter and deals with embedded primary solar energy equivalents, also referred to as “solar energy footprint”. Other related terminologies include the cumulative energy demand and embodied energy. Interestingly, while energy use efficiency has been widely explored in apple orchards in Iran and Turkey, energy or emergy footprint research in apple orchards is scare in both New Zealand and overseas.

2.3.3 Eco-efficiency

Ratio approach

The ratio approach usually defines eco-efficiency as a ratio of social-economic performance to environmental impact (Müller et al. 2015). The numerator is a measure of the socio-economic performance in terms of profit, yield, labour, or foreign workers, for example, and the denominator is a measure of the environmental impacts, such as greenhouse gas emissions, nutrient leaching, waste, biodiversity loss, and ecotoxicological impacts (Clothier et al. 2021). In some literature, the ratio is also termed as eco-efficiency which can be confused with the concept of eco-efficiency. Schaltegger & Burritt (2017) suggest a distinction can be made between eco-efficiency as a concept and as a ratio figure, although these two are linked. Note that sometimes only productivity was considered in eco-efficiency analysis, for example, by using index of weighted agricultural productivity (IWAP) (Suzigan et al. 2020).

Eco-efficiency using the ratio approach has been widely reported. For example, Müller et al. (2015) defined eco-efficiency on an area basis as New Zealand dollar net profit of kiwifruit per kilogram of greenhouse gas emissions (CO_2-eq) in New Zealand. They revealed fertiliser use and the nitrogen-associated emissions as hot spots for greenhouse gas emissions, and that the eco-efficiency of organic orchards was significantly higher than that of orchards with integrated pest management. The ratio approach is easy to understand, calculate and communicate, and not only environmental performance but also economic performance can be considered. However, the ratio approach is used only if numerator and denominator can be integrated into a certain value. Therefore, usually only one environmental impact category can be considered. For this reason, several studies have attempted to create a single score for the environmental impact of wheat production by using a weighting approach (Masuda 2016). A weighting approach can aggregate the normalised indicator results for each environmental impact category, with weighting factors assigned according to their relative importance. However, weighting factors that are based on value choices are affected by subjective and political influences, and a lack of knowledge on the impacts of resource consumption and pollutant emission complicates the derivation of weighting factors.

Life cycle assessment

Life cycle assessment (LCA) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service (ISO 2006; Vásquez-Ibarra et al. 2020). Introduction of LCA analysis can be found in LCIA Recommended Indicators — The Life Cycle Association of New Zealand (Life Cycle Association of New Zealand 2023b). The basic structure of LCA developed by the society for the environmental toxicology and chemistry (SETAC) included the following four arrangement: goal and scope definition, inventory analysis (LCI), impact analysis (LCIA), and interpretation (Figure 5). The most used method for LCIA was CML, ReCiPe, and IPCC (Vásquez-Ibarra et al. 2020). A detailed introduction of LCA is given by Jacob-Lopes et al. (2021).

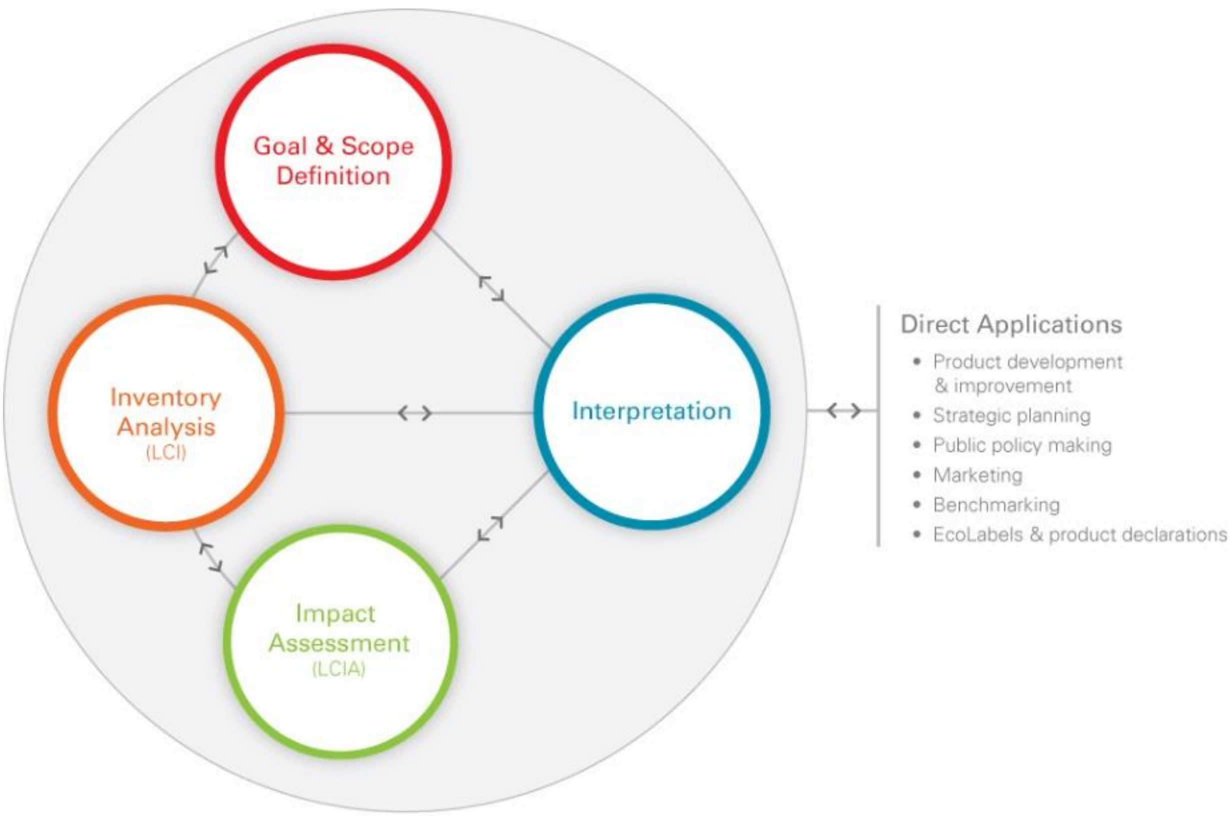

Figure 5. Four different phases of life cycle assessment (LCA) (Life Cycle Association of New Zealand 2023a).

Indicators suggested for LCA studies conducted in New Zealand include global warming potential, stratospheric ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential-elements, abiotic depletion potential- fossil fuels, particulate matter formation potential, water scarcity footprint, toxicity potential-human health (cancer), toxicity potential-human health (non-cancer), toxicity potential-ecosystems, land transformation potential, and ionising radiation potential. In the LCA analysis, both midpoint and endpoint indicators were considered. Midpoint indicators are used to measure the environmental impacts that occur during a particular stage of the product or process, and endpoint indicators, on the other hand, are used to measure the environmental impacts that occur as a result of the product or process. For example, the midpoint will assess the amount of greenhouse gas emissions from the use of equipment, such as tractors, during production, while the endpoints will assess the potential effects of greenhouse gas emissions on climate change.

Current studies using LCA mainly focus on greenhouse gas emissions that relate to global warming potential. For example, the carbon (CO_2-eq) footprint of kiwifruit was calculated for the Bay of Plenty region using LCA (Müller et al. 2015); greenhouse gas emissions (CO_2-eq) of apple production in New Zealand (expressed as CO_2-eq per kg apples) during both production and postharvest were calculated in 2009 based on agricultural input data from 59 growers across three regions (Hawke's Bay, Nelson and Otago) (Hume et al. 2009). While there is no maximum number of indicators that can be considered within a single study, it has been recognised as important to consider a minimum of two (and preferably more) in order to minimise the potential for burden-shifting (i.e. the phenomenon where reducing the impact of one environmental indicator leads to an increase in the impact of another environmental indicator). For example, suppose a company decides to reduce its greenhouse gas emissions by switching to a renewable energy source. If this renewable energy source requires more water for production than the previous energy source, the company may end up shifting the burden of their environmental impact from greenhouse gas emissions to water use. However, in most cases, eco-efficiency using LCA approaches tends to focus on the environmental challenges in isolation (Suzigan et al. 2020). The most frequently used environmental indictors in the LCA method are global warming potential (GWP), eutrophication potential and acidification potential, but other environmental indicators such as water use and energy use have also been included (Vásquez-Ibarra et al. 2020). The LCA method is significantly biased towards the assessment of environmental effects, neglecting the assessment of economic efficiency (Kuosmanen & Kortelainen 2005).

Footprint concept comes earlier than LCA. It is generally recognised that footprint family is more pressure oriented (e.g. resource use and waste production) and the LCA approach is more impact oriented (e.g. the midpoint or endpoint impacts to the ecosystem and human health). Because of this perception, LCA is usually preferably used over footprint. However, these two concepts have already penetrated each other, and a lot of debates arise in terms of the consideration of environmental relevance (Einarsson & Cederberg 2019; Vanham et al. 2019; Matuštík & Kočí 2021). Using the nitrogen footprint as an example, Einarsson & Cederberg (2019) even argued that there are challenges to developing a LCA-compatible impact indicator for the footprint indicator for three reasons: 1) existing research on the many and qualitatively different impacts of nitrogen pollution needs to be considered; 2) understanding whose values and priorities are to be represented in the footprint need to be clear, but the most stringent requirement on environmental relevance one can hope to meet is that an indicator to most stakeholders is reasonably representative of their concerns; and 3) it is by no means necessary to aim for environmental relevance.

Data envelopment analysis

Data envelopment analysis (DEA) is a linear programming based technique for assessing the relative efficiency of a set of units known as Decision Making Units (DMUs), such as a country, region or farms (Vásquez-Ibarra et al. 2020). The efficiency of a DMU is measured by the ratio between its productivity and the productivity of DMUs that display the best possible combination of products and inputs, establishing an efficiency frontier (Suzigan et al. 2020). It provides a measure of relative efficiency, which identifies the efficient and inefficient observed units. Kuosmanen & Kortelainen (2005) argued that DEA models have the advantage "to account for substitution possibilities between different performance criteria and its independence of subjective aggregation weights". In other words, DEA is an objective model in which the weights of economic performance and environmental impacts are allocated in the best possible manner to achieve the highest eco-efficiency score, regardless of subjective orientation. A decision-making unit is considered eco-efficient when no other weight-combination of economic performance and environmental impacts can result in a better eco-efficiency score.

DEA methods differ with LCIA methods, environmental indicators, system boundaries, DEA models, and returns to scale. Currently, DEA can be applied choosing between three different approaches: the output-oriented model, the input-oriented model, or non-oriented. The first defines the ability of the DMU to reach the highest level of outputs from a given combination of inputs; the second, instead, defines the ability of DMU to use the least possible amount of inputs to obtain a given output (Reinhard et al. 2000), and the third focuses on improvement of both inputs and outputs (Cooper et al. 2007). Both constant returns of scale (CRS) and variables returns to scale (VRS) can be considered. The CRS assume that, at the production possibilities frontier, any variation in inputs produces proportional variation in outputs. In the VRS model, the property of proportionality between inputs and outputs is replaced by a convexity property, which considers increasing or decreasing returns to scale at the efficiency frontier. It appears to be the most applied methodology in the literature. After 2010, DEA has emerged as the more dominant method for assessing eco-efficiency in agriculture (Suzigan et al. 2020). Software is available for DEA analysis, such as DEA-Solver-PRO™ (SaiTech 2022), STATA 15 software (StataCorp 2017), and DEA Solver Pro 13.2 (He et al. 2018).

Globally, DEA has been widely applied in agriculture, including horticultural sectors (Coluccia et al. 2020; Vásquez-Ibarra et al. 2020). A detailed literature review on DEA method in the agriculture sector was conducted by Coluccia et al. (2020). The information summarised includes author(s), year, title, area of study, input variables, output variables, and aims of the study. Suzigan et al. (2020) compared the productivity, technical efficiency, environmental efficiency, and eco-efficiency (considering both technical and environmental aspects) for different states in Brazil. The results indicated that the higher productivity areas (southern and South-Eastern regions) corresponded to lower environmental scores and eco-efficiency. Coluccia et al. (2020) used the DEA methodology to evaluate the eco-efficiency of the Italian agricultural sector, as an index useful for emphasising the differences among some national geographical areas. Pang et al. (2016) assessed agricultural eco-efficiency of different provinces in China using DEA and the Theil index approach. They found that agricultural eco-efficiency is mainly affected by pure technical efficiency, and that highly efficient areas are mainly concentrated in the densely populated areas, i.e. the economically developed areas (except Tibet). Bournaris et al. (2019) measured operational efficiency of glasshouse farming by focusing on four different vegetables (cucumber, eggplant, pepper, and tomato) in Greece using DEA. Most DEA analyses used inventory data (resource use and waste production) as inputs with a few exceptions that environmental impacts were used (Masuda 2016). For example, in the study of Coluccia et al. (2020), available data from 2004 to 2017 were collected for 21 Italian regions. These data included the most important input variables that influence agriculture, i.e. Labour, Gross Capital, Land, Fertiliser, and Irrigation Area, and output variable, i.e. agricultural production. The DEA method provides for a multifactor productivity for measuring the relative efficiency of decision-making units (i.e. region). Using this method, the distance between the best practice frontier for the best possible production in the considered sample was computed. Then the obtained values were transformed into a measure of efficiency normalised in the interval [0, 1]. Two models, namely the output-oriented and input-oriented models, were used to measure the relative efficiency of decision-making units (DMUs), which in this case were regions. The output-oriented model measured the ability of the DMU to reach the highest level of outputs from a given combination of inputs, while the input-oriented model measured the ability of a DMU to use the least possible amount of inputs to obtain a given output (Coluccia et al. 2020). The results showed a better orientation towards saving resources for the southern Italy and a greater orientation towards productivity for the northern Italy. However, most of the environmental effects were not from direct measurements but calculated from inventory data.

While outputs in most studies are related to production (desirable outputs), a few studies focus on the undesirable outputs related to environment (Khoshroo et al. 2018; Gatimbu et al. 2020), or both desirable and undesirable outputs (Mihci & Mollavelioglu 2011; He et al. 2018). The results obtained from DEA analysis can be influenced by the selection of input and output variables used in the analysis. If certain important variables are not included or are incorrectly measured, it can affect the accuracy of the results. In other words, the quality of the data used to calculate the efficiency scores can impact the reliability of the DEA results. Therefore, it is important to carefully select the appropriate input and output variables when conducting a DEA analysis to ensure that the results are meaningful and accurate. In agricultural systems, soil health plays an important role in the productivity and environmental performance and it varies spatially. However, it’s not been considered for evaluating eco-efficiency, which can bias the results. In New Zealand, the DEA method has been used in dairy farming systems for investigating energy efficiency (Ilyas et al. 2020) and in the forest harvesting sector for measuring productivity (Obi & Visser 2020).

Compared with LCA, which has a more micro-analytic approach, generally applied to assess the environmental impacts of products and processes, DEA is more focused on the efficient combination of both economic value and environmental impacts, with no subjective weight attribution, has a more macro perspective and is mostly applied to decision-making units (DMU), such as farms (when analysing agricultural eco-efficiency), municipalities, regions, and countries. The differences found in these two methods also lead them to diverge in dataset choices. Primary data prevail in the LCA method, whereas secondary data are dominant in DEA. Nevertheless, these two techniques share a wide range of economic and environmental variables—although both usually fail to incorporate the social dimension of sustainability into the eco-efficiency analysis. Now it’s increasingly popular to combine LCA and DEA for evaluating the co-efficiency of an agricultural system. For example, eco-efficiency of wheat production in Japan at a regional scale was measured using a combined methodology of LCA and DEA (Masuda 2016). The LCA was conducted to quantify the environmental impacts including energy consumption, global warming potential, acidification potential, and aquatic eutrophication potential, for the DEA analysis. The input-oriented slacks-based measure of efficiency model with variable returns to scale was used to measure the eco-efficiency indicator of production. In this model, output was wheat yield and inputs were determined to be global warming potential and aquatic eutrophication potential using correlation analysis for avoiding redundancy of DEA inputs. This study showed that eco-efficient wheat production was attained when a just adequate rate of nitrogen fertiliser relative to wheat yield was applied to farmland. This study also highlights that the mitigation of aquatic eutrophication caused by the excessive use of nitrogen fertiliser is an important factor in improving the eco-efficiency of wheat production (Masuda 2016).

While most studies focus on large scales (e.g. region or nation), studies at farm scales also exist. For example, eco-efficiency at small-scale family farms as the principal DMUs of horticulture in southeast Spain was analysed using DEA method (Godoy-Durán et al. 2017). In this study, several combinations of environmental pressures including water scarcity, chemical contamination, waste management etc were considered as input variables, and economic output was considered as output variable. The aim of this study was to find a balance between economic output and the use of natural resources. The results revealed that the farms in the sample could reduce their environmental pressures by 11%, while maintaining their economic performance (Godoy-Durán et al. 2017).

2.3.4 Comparison of different KPIs

All KPIs for environmental assessment are summarised in Table 9. Through the literature review, three types of KPIs can be identified: 1) Resource use efficiency; 2) Environment footprint; and 3) Eco-efficiency analysis. For each type, various approaches and indicators have been proposed, each KPI has their own advantage and disadvantages as discussed in section 2.3.1–2.3.3. In general, for each type of KPIs, case studies of including both environmental and biological (or economic) aspects can be found in the literature. Conceptually, all KPIs are easy to understand and communicate. They provide valuable insights for managing specific environmental concerns such as water quantity, nitrogen use, and greenhouse gas emissions. However, assessing multiple environmental performance aspects simultaneously can present challenges.

Table 9. Comparison of different key performance indicator (KPIs) and methodologies to assess environmental performance of horticulture land uses.

Category	KPI	Environmental issues considered	Data required	Cumulative effects and scaling up to different spatio-temporal scales	Advantages	Disadvantages
Resource use efficiency	Water use efficiency	Water quantity	Water use (evapotranspiration), crop production	Can be determined at various spatio-temporal scales depending on data availability	Easy to measure and understand; both water use and production are considered; can be used to optimise water use	Water scarcity not considered; environmental impacts not considered; not ideal for comparing different crops
	Nutrient use efficiency	Potential nutrient losses	Nutrient input, nutrient in soil and plant, crop production	(See above)	Reflect the efficiency of nutrient use; indicate the potential risk of nutrient losses; easy to understand and calculate	Single element considered; high nutrient use efficiency does not necessarily mean high production; not directly related to nutrient losses and environmental damage; various indices used which may affect the communication
	Energy use efficiency	Energy use	Agricultural inputs (e.g. human labour, water, electricity, fuel, machinery, chemicals [fertilisers, pesticides] and farmyard manure land area), crop production	(See above)	Easy to calculate, understand and communicate; can potentially reflect environmental problems (e.g. greenhouse gas emissions)	The real environmental problem may depend on the source of energy and the way it is used; may not fully capture the environmental impacts
Environmental footprint	Water footprint	Water quantity, quality	Precipitation, irrigation, evapotranspiration, pollutant load, ambient water quality standard, natural concentration of the pollutant in the receiving water body, crop production	(See above)	Easy to understand and calculate; water use from precipitation and irrigation can be distinguished; water scarcity can be considered	Usually indicator of water consumption rather than environmental impact considered in WFA; results are affected by method
	Carbon footprint	Mass units of CO_2 equivalent related to global warming potential or global temperature change potential (climate footprint)	Various GHGs (usually calculated from agricultural input data with emission factors), crop production	(See above)	Intelligibility and ability to be communicated, related to impacts on climate change (e.g. global warming)	Not consistent in terms of GHGs considered; high variations in results expected; often used as the only indicator of environmental performance Emission factors and GWP may vary over time between studies and between countries
	Nitrogen footprint	Reactive nitrogen (Nr) released to the environment	Depending on approaches: total Nr consumed in diet, nitrogen use efficiency,	(See above)	Can be used to derive nitrogen pollution reduction strategies	A rather recent indicator; many challenges to be tackled, such as data availability, how to

Category	KPI	Environmental issues considered	Data required	Cumulative effects and scaling up to different spatio-temporal scales	Advantages	Disadvantages
			nitrogen pollution embedded in international trade			discriminate nitrogen species, system boundaries, or the transformation of Nr through nitrification and denitrification
	Biodiversity footprint	Biodiversity loss caused by land use or product or other drivers, local biodiversity	biological organisms of a system	Can be determined at various spatio-temporal scales depending on data availability	Can be used to explore land use or management practices impact	Need multiple simplifications assumption and data limitations; multidimensional concept that is impossible to measure with a single unit
Eco-efficiency	Ratio approach	Can be all environment of interest (production per single or multiple environmental index)	Economic output, production inputs, environmental outputs (at least one variable from the three categories)	(See above)	Can incorporate many indicators, both economy (productivity) and environmental outcomes can be considered; simple to compute, easy to comprehend; can assess a specific aspect of a DMU's performance;	Social dimension usually not included; data availability can be a problem; can't simultaneously incorporate multiple inputs & outputs; hard to standardise various environmental items; implicitly assume constant returns to scale which may not apply in real settings; may not be able to decompose performance into several sources; don't identify benchmarks or role models for inefficient DMU; partial measures of performance
	Life cycle assessment	Multiple impact categories, but usually presented individually	More primary data (e.g. agricultural input) focused	(See above)	Focus more on environmental impacts; multiple impact categories can be considered; life cycle thinking;	Tends to focus on the environmental issues in isolation (Suzigan et al. 2020); requires large amounts of hard-to-find data with consequent approximations; weighting problem; environmental impacts overlapped; usually neglecting economic efficiency assessment
	Data envelopment analysis	Can be all environment of interest	More secondary data focused, economic and environmental inputs and outputs	(See above)	Aggregating different environmental impacts and does not require explicit weights; can identify best-practices & determine targets for inefficient DMUs	Relative efficiency; limited by data availability; variables considered vary a lot with studies; results may depend on the input/output selected, so some important factors such as soil health being ignored can complicate the results

A lot of comparisons are made between different environmental KPIs in terms of their advantages and disadvantages. When evaluating environmental impact, comparisons and debates are made if the KPIs are more pressure (e.g. footprint) or impact-oriented (e.g. LCA approach). Matuštík & Kočí (2021) commented that "if footprint is usually not represented in the context of sustainability analysis, the related results often lose a clear physical interpretation. It seems that for public presentations and comparative purposes, especially regarding products or services, the impact-oriented footprints would be more appropriate to avoid misinterpretation; the inventory footprint concept might be more useful for detailed sustainability studies, as they are more convenient to be linked to the concept of carrying capacity or planetary boundaries." For evaluating eco-efficiency, the two major methods (LCA and DEA) are usually compared. According to Suzigan et al. (2020): "The LCA is generally focused on the assessment of the environmental impacts of products and practices, neglecting the assessment of the economic efficiency. DEA is mostly used to measure the eco-efficiency of decision-making units (DMUs), such as farms, regions, or countries, and has no subjective focus on neither technical nor environmental performance. Both methods share a wide range of economic and environmental indicators but usually fail to incorporate the social dimension of sustainability into the eco-efficiency analysis."

The common disadvantages of existing KPIs can be summarised as:

- Only a limited number (one in most cases) of environmental issues can be considered in a single metric. Therefore, they can't be used to capture the full picture of the environmental issues, and more unified/comprehensive approach to eco-efficiency measurement is needed. Although DEA approach can be used to unify various indicators, the result reliability highly relies on the understanding of the responses (e.g. output to input) in the system, and the demanding on the coding and mathematical calculation is relatively high.
- Most studies on each type of environmental KPIs are based on management input data (inventory) without considering the environmental impacts. Although environmental impacts can be considered in some KPIs (e.g. LCA or LCA- compatible footprint), they are usually based on some conversion factors (e.g. emission factors for greenhouse gas) which need yet to be verified.
- Limited availability of reliable and harmonised data is the main hurdle for developing and verifying environmental KPIs. Lower availability of reliable data for smaller-scale units (e.g. farms and municipalities) is a foremost limitation for eco-efficiency analysis (Suzigan et al. 2020).
- Some KPIs are overlapping to different extents (Vanham et al. 2019), therefore, it's often challenging to combine various existing KPIs to a single one. For example, the N_2O emissions component is included in both the carbon and nitrogen footprint.
- It seems that the debates on the preference of pressure-oriented or impact-oriented KPIs never end, which indicates that none of the existing KPIs is fit-for-all-purpose.
- Environmental KPIs are used to evaluate the sustainability of an agricultural system, however, eco-efficient unit is not necessarily sustainable when the four physical dimensions (space, time, resources, products) and all three pillars of human development (economic, environmental, social) are regarded (Suzigan et al. 2020).This is because eco-efficiency is a relative measure, which compares the performance of similar products, processes or peer decision making units against best practices.

- Many studies on environmental KPIs focus on large scales (e.g. national, global) by ignoring the site-specific environmental impacts under a specific context of soil, topography, climate and management practices, which tends to be important for improving environmental performance at the orchard scale.
- The effects of management practices such as soil compaction on environmental performance including nitrate leaching, N_2O emission, contaminants through drainage and runoff has been comprehensively reviewed (Hu et al. 2021). However, despite this large body of knowledge, the impacts of management practices on environmental performance are usually not considered in existing environmental KPIs used for evaluating environmental impacts.
- In most cases, environmental KPIs mainly focus on environmental issues. Although economic pillar is also considered in some KPIs, lack of social value evaluation is a big gap. In many cases, it's not clarified whose values and priorities are to be represented in the environmental KPIs.

2.4 Conclusions

- The key environmental issues may be different for different horticultural crops. To assess all the environment of interest for each crop can be too costly and hence not practically feasible. Therefore, environment of interest and associated environmental metrics should be prioritised for data collection. For example, vegetable farms are usually intensively managed which may involve intensive tillage and high water and nitrogen inputs. Therefore, soil health, water quality, and greenhouse gas emissions may be the main focus. In the pipfruit sector where low rates of fertilisers are applied, however, water quality may be of lower priority than weed, pest and disease management. Likewise, more attention on water quantity should be given to regions with greater water limitations such as Canterbury, Marlborough, Hawke's Bay, Northland and parts of the Auckland region.

- Both water-use by crops via evapotranspiration and water loss via drainage and runoff needs to be quantified. Quantification of water use and loss not only on an annual basis but also temporally (e.g. seasonally) will be useful to fully characterise the potential impacts of water use. Some qualitative data such as irrigation system, tools/systems to assess daily water requirements, adoption of measures to conserve water loss or reduce water demand are also important to understand the potential efficiency of water use. In regions with water limitation, other water uses such as frost protection and chemical spray may not be ignored. However, it is more important that there is access to frost protection although there might be other methods available.

- Water quality is associated with contaminations by nitrogen, phosphorous, pesticides, sediment, and untreated discharge from indoor growing systems. Understanding the key contaminants source and terroir for various horticultural land uses is crucial for prioritising the assessment. For example, while nitrate leaching is important in vegetables with high nitrogen inputs, pesticides pollution should be the main focus for perennial crops especially under the integrated pest management systems. Drainage losses should be the focus on flat land and well drained soils, while surface runoff losses should be the focus on sloping land especially clay and compacted soils under relatively high rainfall.

- Soil heath and soil quality is the base of regenerative agriculture as soil health is closely related to not only crop yield, quality, but also environmental performance. Although soil health is well defined, its characterisation is quite challenging. In New Zealand, a minimum data set including total C, total N, mineralisable N, pH, Olsen P, bulk density and microporosity has been proposed to assess soil quality. However, we are not confident that these properties are sufficient to quantify soil health in all horticulture land uses. Therefore, ecosystem services-oriented approach should be used to characterise soil health. For example, while soil micro-organisms may be a good indicator for soil health in wine production, soil macro-porosity can be a good indicator for soil health in soils with poor soil structure and high nitrogen inputs (e.g. intensive vegetables) where risk of N_2O emissions can be high.

- Biodiversity plays a crucial role in supporting ecosystem services, and it can be classified into various types. Assessing biodiversity in agricultural settings can be facilitated by examining the aquatic ecosystems present on farms. The condition and characteristics of these aquatic ecosystems can provide valuable insights into the overall farm environment and the biodiversity it supports. Alpha diversity, gamma diversity, and community similarity are the three commonly used measures of biodiversity. Ecological studies can have various scopes and focus depending on research questions and goals of the study, ranging from single species or group of related species to multiple taxonomic groups or entire ecosystems. The ecological structure approach can also be used to assess the impact of land use on biodiversity. Overall, understanding and monitoring local ecosystems and ongoing conservation efforts are crucial to protect and restore habitats for key species and to sustain the ecosystem services that biodiversity provides.

- Agriculture is a significant contributor to greenhouse gas emissions in New Zealand. Simple accounting-based models are widely used to estimate greenhouse gas emissions. For example, tools proposed by He Waka Eke Noa would calculate N_2O emissions based on fertiliser nitrogen inputs only and do not account for nitrogen inputs from residues left following harvest or through pruning or mowing. Nitrogen inputs from decomposition of residues can be as large and greater than the nitrogen inputs from fertiliser. New Zealand has 11 approved greenhouse gas emissions tools available to growers and farmers. All these tools are based on greenhouse gas inventory type calculations and do not take into account interactions with environmental factors. While there is an interest by growers to account directly for carbon sequestration on farms and orchards, the ability to quantify this is not yet available.

- Effective weed, pest, and disease control is essential for maximizing productivity and profitability in horticulture. Integrated management systems that combine chemical, biological, and cultural methods are increasingly being used to manage weeds, pests, and diseases. While chemical methods are cost-effective and quick-acting, they can have negative impacts on human health, non-target organisms, and the environment. It is important to consider relevant standards such as maximum residue levels and threshold levels of spray when conducting weed and pest control. Metrics and attributes for measuring weed, pest, and disease management at a farm level mainly include the number of sprays, type of spray, area sprayed, spray rate, and spray efficiency. However, environmental performance and impacts are difficult to quantify and require further exploration.

- Heavy metals are known to occur in horticultural land use, posing risks to human health and the environment. While some metals are essential for plant growth, high concentrations of heavy and toxic metals in soil and plants can be harmful. Therefore, there are guidelines and regulations in place to monitor and manage heavy metal concentrations in horticultural soils.

In New Zealand, MPI sets maximum permissible rates for heavy metals in soil and water, and growers are required to test their soil and water regularly to ensure compliance. The Cadmium Management Group and its members have produced reports and reviews to help manage cadmium in New Zealand. Metrics for heavy metals include agrichemical sprays or fertilisers, which are widely used to control pest and disease or stimulate plant growth in horticulture. However, agrichemicals usually contain heavy metals, which can potentially contaminate the environment, making the application of approved agrichemicals in a way that gives the highest possible spray retention on the target important for minimising contamination of the environment.

- Mahinga kai refers to the traditional Māori practices of managing and utilising natural resources for food, medicine, and other needs. Mahinga kai and Tikanga Māori are interconnected in a holistic way in Māori culture. The principles of Tikanga Māori guide the sustainable practices of mahinga kai, ensuring that resources are used in a way that is respectful, balanced, and in harmony with the natural world. Mahinga kai practices have been passed down through generations and continue to play an important role in the lives of Māori communities. The protection and enhancement of mahinga kai is crucial for sustainable environmental management, access to clean and healthy kai, and securing food in a sustainable way. Growers who require land use consents to farm have a responsibility to address mahinga kai and be aware of the mahinga kai values and risks on their land. Guidance has been provided by various organisations and agencies (e.g. Ministry for the Environment, Australian and New Zealand Environment and Conservation Council) on how to relate existing guidelines and regulations to freshwater invertebrate and fish species traditionally used for food gathering. Research is also required to understand the potential sources of chemical contamination and nutrients from horticultural activities on water quality and mahinga kai.

- Horticulture in New Zealand also faces several other environmental challenges that need to be addressed to ensure sustainability. These are associated with waste management, greenhouse industries, burning-related air quality, natural fertiliser management, and plasticulture and recycling. A circular economy approach can be used to guide waste management. The greenhouse industry's significant environmental impact, driven by its reliance on fossil fuels and wood, necessitates responsible and sustainable management of CO_2 enrichment. Preventing CO_2 leakage from the greenhouse is one example of mitigating these effects. Clear guidelines and best practices are needed in New Zealand for using outdoor burning as a land management tool to limit the adverse health and environmental effects caused by smoke and odour. Using natural fertilisers in horticulture requires careful management to minimise the risk of microbial pathogens contaminating produce, which involves controlling quality, composting, and appropriate application methods. Horticultural plastic use requires careful consideration due to concerns regarding soil health, biodiversity, productivity, and water contamination, with biodegradable plastics presenting potential alternative solutions, but further research is required to evaluate their efficacy and environmental impact, and alternative solutions are being explored.

- Efforts are being made with the support of MfE to develop a simple but robust risk matrix for evaluating environment issues such as nitrogen loss. Such examples in New Zealand include the Tiaki programme nitrogen-risk scorecard developed for the dairy sector. We suggest both components of a system (e.g. climate, soil and topography) and exposure (e.g. management practices) should be considered in developing a risk matrix. The degree of mitigation required for each responsible management practice should also be assessed to guide if mitigation is needed to reduce the risk. To obtain a final score of a cropping system, the contributions from different factors within/between components should be derived from either expert knowledge or process-based modelling (e.g. APSIM) under different scenarios. In addition, trade-off between nitrogen leaching and surface runoff should be considered.

- Key performance indicators (KPIs) are recognised that can assess environment performance together with others (e.g. production, social wellbeing) from the aspects of sustainability. Three groups of KPIs can be categorised, including resource use efficiency based, environmental footprint based, and eco-efficiency. Most KPIs (such as resource use efficiency and environmental footprint) can only be used to assess one environment topic (e.g. greenhouse gas emissions) plus one outcome (e.g. production) because different environmental performances are hard to integrate as one value due to the difficulty in weighting. With the purpose to compare different growing systems for the same crop or different crops in terms of sustainability, the full pictures of all key environmental issues should be comprehensively understood. From this aspect, data envelopment analysis in combination with life cycle assessment can be a promising tool.

3 Models to assess environmental performance

3.1 Existing horticulture system models

Farm systems sit within the broader environment and when it comes to assessing environmental performance, we are interested in how activities on farm influence the balance of negative and positive outputs to the environment (Figure 6). This may be approached with a mixture of simple or more detailed approaches. Simpler approaches use simple models that relate grower activities and farm system characteristics to potential benefit or harm. For example, applying irrigation and nitrogen fertiliser will increase the risk of nitrate leaching to the environment. A straightforward risk assessment, such as utilising a risk matrix (see Section 2.2), could record number and amount of irrigation and fertiliser applications. However, these practices also increase production which underpins human health and wellbeing. It is difficult to assess overall environmental performance with only simple approaches as they do not give a clear picture of relative harm and good. To take a more detailed approach, a number of farm outputs may be quantified by collation of existing data and/or the collection of additional data. Outputs such as drainage, runoff, and emissions are impractical to measure directly. This is where detailed modelling enters the process. Models take measurable input data that quantify grower activity and farm systems characteristics and use it to predict outputs that are not practical to measure in non-research contexts. Furthermore, models may be run to reflect actual situations for quantifying current environmental performance, but also run in hypothetical situations or scenarios to assess the potential impact of alternative approaches. This section of the report provides an overview of modelling options available for estimating farm outputs.

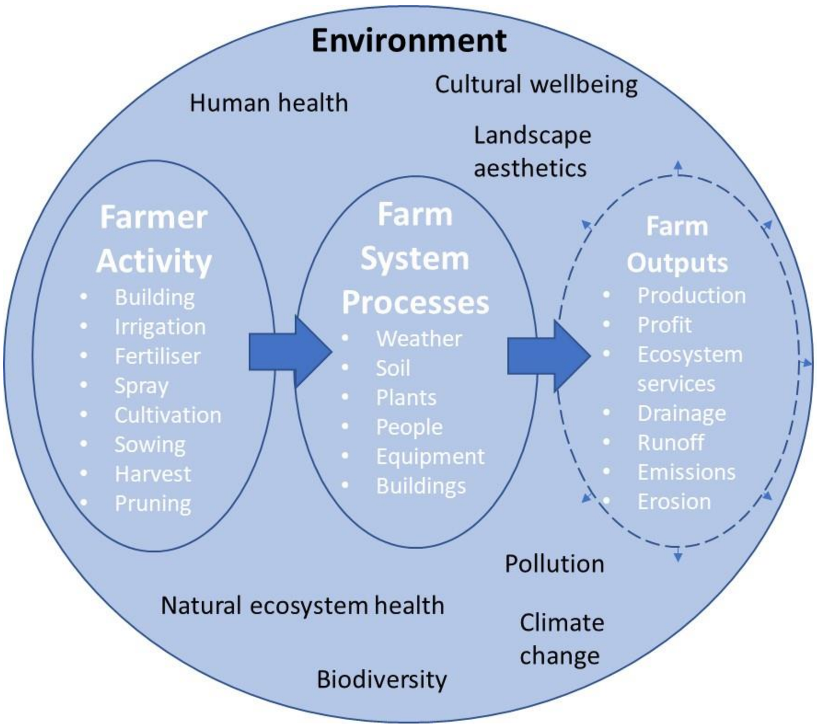

Figure 6. Framework for assessing the influence of grower activities on farm outputs.

There is a wide range of models that may be used for modelling environmental impacts. All have some similarities and differences, and none are yet complete for the job of modelling all environmental impacts and productivity metrics of interest in all horticultural scenarios in New Zealand. All require expert operators to ensure input data and configurations are defensible. There is a lot of overlap in scope and function of models, so we group them into seven categories and provide a listing of the model options in each category and a description of the features of each category of model.

1. **Farm scale accounting models** have been developed to capture and collate farm activities and compute metrics of extent of activities that can cause negative environmental impacts through basic summation and application of multipliers.
2. **Basic farm models**, which have been developed for the simulation of variables at the whole farm scale. They take account of land use, management, soil, and climate information but are relatively simple to reduce input data and user expertise requirements.
3. **Deterministic farm system models**, which have been developed for the simulation of variables at the field scale but may be aggregated to provide farm scale predictions. They provide more detailed handling of soil, plant, and management processes allowing for more exact representation of the situation being simulated. However, they require more input data and a higher degree of user expertise to operate.
4. **Single crop decision support systems**, which have been developed to aid in the management of a specific crop. They have a more exact representation of the water and nutrient demands of specific crops and aim to provide pre-establishment and in season information to guide better nutrient or irrigation practices.
5. **Detailed process models**, which have been developed to pay close attention to all the processes underlying specific facets of a farm system such as soil water infiltration and percolation.
6. **Catchment erosion/sediment models**, which have been developed to estimate erosion processes and sediment discharge from a catchment area.
7. **Digital farm shadow** is a concept not yet available for use but would combine aspects of most of the models above to give a digital representation of a farm system and provide estimates of environmental performance from detailed farm status input data.

A summary of the characteristics of each group of models is given in Table 10 and a more detailed description of each type is given in the following sections. A model can only be useful in the hands of a suitably skilled operator. It is easy to make a model give results but takes a high degree of expertise, experience, and diligence to ensure that all the input data being provided are appropriate and correct, all the configuration settings are sensible and the results that are being produced are defensible. Because of this we have made comment on the accessibility of models considering both access to the executable code but also expert users who are able to drive it.

Table 10. Comparison of features of each type of model.

	Farm scale accounting	Basic farm model	Deterministic farm system model	Single crop decision support system	Detailed process models	Erosion/Sediment models	Digital farm shadow
Example Tools	ProductionWise HortNZ tool Cool farm tool	Overseer	APSIM SPASMO	Potato calculator Wheat calculator	Hydrus DNDC GrowIMP	NZeem SedNet	-
Inputs	Location Management records	Location Management records Soil Climate	Management records Soil Climate	Management records Soil Climate	Management records Soil Climate	Geography Land use Soil Climate	Location Geography Management records Soil Climate
Drainage	May determine risk	Monthly estimates	Daily estimates	Daily estimates	Hourly estimates	-	Daily estimates feasible
Runoff	May determine risk	-	Daily estimates from simulation point	Daily estimates from simulation point	Hourly estimates	Annual or monthly averages	Daily estimates feasible
Nutrient leaching	May determine risk	Monthly estimates of long-term average	Daily estimates	Daily estimates	-	-	Daily estimates feasible
Nutrient runoff	May determine risk	-	Daily estimates from simulation point	-	-	-	Daily estimates feasible
Sediment runoff	May determine risk	-	-	-	-	Annual long-term averages	Daily estimates feasible
CO_2 emissions	Estimate whole farm losses using emissions factors	Estimate whole farm losses using emissions factors	Daily estimates of soil carbon change in response to climate and management	-	-	-	Daily estimates feasible
N_2O emissions	Estimate whole farm loss using emissions factors	Estimate whole farm losses using emissions factors	Daily estimates of emissions in response to soil and climate	-	DNDC predicts losses hourly	-	Daily estimates feasible
Productivity	May record actual production as input	User input used for modelling	Yields predicted in response to soil, climate and management over crops duration	User input or predicted	GrowIMP predicts growth and development hourly	-	Yields predicted in response to soil, climate and management over crops duration

	Farm scale accounting	Basic farm model	Deterministic farm system model	Single crop decision support system	Detailed process models	Erosion/Sediment models	Digital farm shadow
Estimates for actual situations	Yes	No – long-term steady state	Daily estimates for any situation where soil, climate and management data are available	Estimates crop demands daily to construct schedule	Yes	-	Yes
Estimates for hypothetical situations	No	No – long-term steady state	Daily estimates using retrospective weather data with hypothetical management	User inputs may be altered to determine impact on schedule	Yes	Hypothetical changes to land use may be represented by changing hydrology or model coefficients	Scenario analysis is feasible
Type of model	Simple annual sums and multipliers for accounting	Steady state, long term average semi mechanistic	Mechanistic biophysical process model	Mechanistic biophysical process model	Detailed biophysical mechanistic process models	Geospatial process model	Integrate geospatial and biophysical process models with annual accounting
Scale	Farm enterprise	Blocks aggregated to farm enterprise	Points aggregated laterally to field or farm	Field	Point or multiple points	Catchment	Farm – subset of catchment for geospatial combined with aggregate of points for biophysical
Dimensions	Non-dimensional	1 dimensional with lateral transfers between blocks	2 dimensional. Depth at each point with lateral transfer possible between points	1 dimensional with depth represented for field	Hydrus (1, 2 or 3D options) GrowIMP – 3D DNDC – 1D	3- dimensional catchment processes	3 dimensional

3.1.1 Farm scale accounting

Example model

ProductionWise is primarily a farm record management system but has been extended to apply emissions factors to estimate greenhouse gas losses from these management records (ProductionWise 2023).

Inputs

ProductionWise takes inputs of most farm activities, crop performance, and stock levels (of crops). The inputs that must be complete and accurate to get an estimate of greenhouse gas emissions are: Crop types and yields; Tractor hours and fuel type; Fertiliser applications, type, and amount.

Outputs

An estimate of CO_2 and N_2O emissions from machinery, electricity consumption and fertiliser use.

Model description

This is a very simple model that uses farm record inputs to determine annual fuel consumption, fertiliser use, electricity consumption and chemical use and applies emissions factors to these to estimate emissions of N_2O and CO_2. It does not simulate CO_2 losses/sequestration from changes in soil carbon as a result of cultivation, crop type, and residue treatments. It also omits soil, environment, and management effects on N_2O emissions, reporting estimating typical values based on fertiliser use. In reality N_2O losses will vary substantially with each fertiliser application depending on the temperature and oxygen status of the soil.

Model accessibility

ProductionWise is available to all FAR levy payers. FAR provide training and support for individual growers to access this system.

Similar models

There are numerous other software platforms that provide environmental accounting based on farm records. The common ones in New Zealand such as FarmMax and E2M are developed specifically for pastoral land uses and are not able to cover cultivated or perennial horticulture.

- Cool Farm Tool is developed by the Cool Farm alliance and aims to help growers make informed decisions to reduce their environmental impact (Cool Farm Alliance 2023). It provides estimates of greenhouse gas emissions (including estimates of soil carbon sequestration), water footprints and biodiversity scores. It takes a range of inputs depending on the metric being calculated:
    - Biodiversity: Cultivation, crop rotation and residue treatment; areas of grassy verges and corners, hedges, water courses, ponds and pools; conservation areas.
    - Water use: Location; irrigation applied; sowing and harvesting dates; soil moisture at planting.

- Greenhouse gases: yield; fertiliser applications (number and type); pesticide applications; Fuel and electricity consumption.

- The HortNZ and MfE tools are simple spread sheets that calculate N_2O emissions from fertiliser and CO_2 emissions from lime and dolomite application inputs (He Waka Eke Noa 2023b).

3.1.2 Basic farm scale models

Example model

Overseer describes nutrient movements on farms (Overseer 2023). The model simulates a farm system of arbitrary complexity (single block or as many blocks as necessary) on a monthly time-step for a 1-year period.

Inputs

Climate: Long term average monthly rainfall, temperature and potential evapotranspiration (PET) required. Accessed from nearest grid point on the NIWA virtual climate network.

Soil: Plant available water capacity in the top 60 cm of soil and drainage characteristics for each farm block. Can be specified directly or gained by selecting an appropriate S-Map soil type.

Management: Planting and harvest months of each crop must be provided for each block that is set up in a farm simulation. Monthly inputs of irrigation (amount) and fertiliser (amount and type) are input by the user.

Outputs

- Annual farm-level nutrient balance including losses to water and atmosphere.
- Predictions of annual greenhouse gas emissions and carbon sequestration.
- Monthly nitrogen and water balance variables.

Model description

Overseer was initially developed as a tool for guiding fertiliser inputs for pastoral farms but has evolved into a system for modelling the nitrogen, carbon and water balances of most farm types in New Zealand including broad acre vegetables, wine grapes, apples, kiwifruit, avocados, and peaches. This evolution has been driven by a demand for farm scale estimates of nutrient loss and greenhouse gas emissions for policy development and implementation and the desire to have all land uses simulated by the same model. Overseer is a relatively simple model in its handling of underlying processes. Importantly, Overseer does not simulate production, it takes this as an input. Its simplicity has allowed it to be parameterised for a wide range of land use types and configured to represent most New Zealand farming systems and minimised the amount of input data required to set up a farm simulation. However, the scientific rigour of the Overseer modelling approach and implementation has received significant criticism which culminated in a recent review (MPI 2023d). Its general finding was a lack of confidence in Overseer’s predictions of nitrogen loss to waterways.

Model accessibility

Access to the model is available by subscription to individual farms and by agreement for research purposes. A moderate amount of expertise and experience is required to ensure reliable simulation results are obtained. Training courses are available through Massey University.

Similar models

We are not aware of other models that simulate farm scale nutrient balance in a similar way for horticultural crops.

3.1.3 Deterministic farm system models

Example model

Agricultural Production system SIMulator (APSIM) (APSIM 2023). APSIM is the most widely used deterministic farm systems model in the world (Holzworth et al. 2015). It has been widely utilised for analysis of crop production and water/nitrogen/carbon balance and is recognised as an option for estimating nitrogen leaching from farms in New Zealand (Cichota et al. 2013; Holzworth et al. 2014; Teixeira et al. 2016; Vogeler et al. 2022). It is able to predict N_2O losses from denitrification and soil carbon losses/sequestration (Vogeler et al. 2013; O'Leary et al. 2016). It also has a fully flexible approach to specifying management and making custom calculations during run time (Moore et al. 2014). This means metrics associated with management practices can be accumulated and factors applied to them to provide additional model outputs.

The fundamental simulation area is a zone which represents a small area of common climate, soil and management. An arbitrary number of zones can be specified and aggregated to form fields and whole farm systems. Simulations run at a daily time step between arbitrary start and end dates. APSIM has generic models for predicting the nitrogen and water balance of broad acre crops (SCRUM) (EN et al. 2016), tree crops (Simple fruit tree model) and specific models for predicting the growth and development of a wide range of crops including wine grapes and potatoes.

Inputs

Climate: A complete set of daily rainfall, minimum and maximum temperature, solar radiation and vapor pressure data are required for the duration of simulations.

Soil: Each zone requires soil information including physical (saturation, drained upper limit, lower limit and air-dried soil water contents, bulk density and hydraulic conductivity), chemical (nitrate, ammonia, urea concentrations and pH) and organic (soil carbon %, carbon to nitrogen ratio). The soil is separated into an arbitrary number of layers specified to an arbitrary depth as is appropriate.

Management: The date and specific information for each relevant management event including sowing (crop type, population, row spacing), harvest (proportions removed and retained in field), thinning/pruning (intensity), irrigation (amount) and fertilisation (amount and type).

Outputs

Data can be output daily or on specific events. All variables may be output but the ones of relevance to the scope of this review are: Irrigation and fertiliser applications, drainage, runoff, leaching, soil moisture content, crop nitrogen uptake, transpiration, evaporation, denitrification, mineralisation, soil carbon and soil nitrogen. Accumulations and multipliers may be applied to outputs during run time so additional metrics can be output.

Model description

The simulations are centred around a soil with most types of crops and managements being able to be specified to make up a farm system. Fluxes of water, nitrogen and carbon to and from each layer of soil are determined each day following internationally established norms in modelling soil processes. Plant growth and development is estimated daily in response to soil and climate conditions and production will decline where water or nitrogen are in short supply. APSIM is under continuous development by an international collaboration of modellers including a substantial contribution from New Zealand. A plant modelling framework has been developed in APSIM to facilitate the development of new crop models.

Model accessibility

APSIM is freely available for download for research purposes and available for commercial use under licence. It requires a high degree of user expertise and experience to obtain reliable results. Training is offered occasionally by APSIM's owners and there are a number of expert operators and developers actively working with APSIM in Crown Research Institutes.

Similar models:

There are numerous models that are similar to APSIM in concept but differ in their code base, formulation, calibration, testing and the range of crops they cover:

- SPASMO (SPASMO 2023): A model developed for studying water and nutrient balances in New Zealand fruit production systems but has been adapted to study a wide range of situations. Accessible through PFR with a limited number of expert users.
- There are numerous other models available internationally but have few or no expert users based in New Zealand.
    - DSSAT (DSSAT 2023)
    - STICS (STICS 2023)
    - CropSyst (Washington State University 2023)
    - AquaCrop (FAO 2023)

3.1.4 Single crop decision support systems

Example model

The Potato Calculator. The Potato Calculator was developed with MPI Sustainable Farming Fund investment to support sustainable potato production. Its model components are similar to deterministic farm system models, but it was engineered to support in-season management of potatoes specifically.

Inputs

As for deterministic farm system models.

Outputs

As for deterministic farm system models.

Model description

In addition to its deterministic modelling components, the potato calculator also included a web-based user interface to simplify the process of configuring and updating information for potato fields. It would be set up at the beginning of the season then updated throughout the year with actual climate data to provide forecasts of when irrigation and fertiliser are required and could provide analysis of stress events and water and nitrogen losses postharvest to provide insights for future improvements.

Model accessibility

The Potato Calculator was made commercially available through CropLogic. However, that business no longer operates/provides horticultural support tools and the model is no longer easily accessible.

Other examples

- The Wheat Calculator; As for the Potato calculator but for Wheat.
- AmaizeN: As for the Potato calculator but for Maize.
- AquaTrac: Developed to provide whole farm irrigation scheduling advice to crop and vegetable growers.
- SVS Vegetable nutrient management tool: Currently under development in the MPI and industry funded project, Sustainable Vegetable Systems (SVS). This tool aims to provide nitrogen fertiliser recommendations for broad acre and intensive vegetable and crop production. The tool aims to ensure a reduction in the losses of nitrogen from the production system.
- Irrigation-allocation calculators: Developed for various Regional Councils, and also used for Environment Agency Abu Dhabi for their Law 5 implementation. It has also been used in a NZ Aid project in Kenya.
- Pesticide Risk Calculator: Approximately 15 years ago a leaching and residue calculator was developed under a Sustainable Management Fund (SMF) for a wide range of pesticides and practices.
- Crop Calculator for water use by field crops, tunnel houses and greenhouses in the United Arab Emirates (UAE) for Environment Agency Abu Dhabi: This includes the water used for cooling where appropriate.

3.1.5 Detailed process models

Example model

Hydrus (PC-Progress 2023).

Inputs

Climate: As for deterministic models but rainfall and irrigation need to be at a sub-daily timestep.

Crop: Daily values of height, leaf area index, albedo and root depth.

Soil: As for deterministic models plus substantial additional information required characterising the shape of moisture release, hydraulic conductivity curves and thermal and chemical properties of the soil.

Outputs

As for deterministic models regarding components of the nitrogen and water balance with a vast selection of additional outputs allowing detailed investigation of water and solute movement processes.

Model description

HYDRUS is a detailed model for the analysis of water flow and solute transport in variably saturated porous media (e.g. soils). The software package includes computational finite element models for simulating the one-, two-, and three-dimensional movement of water, heat, and multiple solutes in variably saturated media. It is widely used in the study of water and solute infiltration and percolation. However, it requires highly expert users, a substantial amount of information for parameterisation and performs many calculations so is slow to execute. As such this and other detailed process models are most likely not suitable to provide estimates of farm-scale environmental impacts.

Model accessibility

Copies of Hydrus can be purchased for research use. A very high degree of operator expertise and experience is required to obtain reliable results.

Other examples

- DNDC (DeNitrification-DeComposition) (University of New Hampshire 2023): a detailed soil process model with a focus on predicting emissions of trace gases including N_2O, nitric oxide (NO), dinitrogen (N_2), ammonia (NH_3), methane (CH_4) and carbon dioxide (CO_2).

- GroIMP: A detailed plant model that explicitly modes the 3-dimensional positioning of organs, interception of sunlight, photosynthesis, carbohydrate transport and organ growth.

3.1.6 Erosion/Sediment models

At the field scale there are large number of management practices that influence erosion losses from susceptible soils (Barber 2014). For example, number, type and timing of cultivation events; treatment of residues; orientation of cultivation and plant rows to slope; duration and timing of fallow periods;

specific mitigation measures. Models for predicting erosion of soil and subsequent sediment discharge from an area are generally developed to predict the long term annual average soil loss from an area based on topography, soil type, climate and land cover (Dymond et al. 2010; Dymond et al. 2016; Donovan & Monaghan 2021; Donovan 2022). As they work at an annual time scale and represent land use at a very granular scale, they are not able to estimate the losses from a specific field for a specific set of climate and management circumstances.

3.1.7 Digital Farm Shadow

A digital shadow is where a sophisticated model is configured to provide a virtual representation of a physical entity (Purcell & Neubauer). Updated data on the activity and status of the physical entity flows into the digital shadow which is then able to provide further analysis and insight of the current state of the physical entity. While there are no working examples of digital shadows of agricultural systems in New Zealand, this is a useful concept for future aspiration. A digital shadow does not need to cover all aspects of the entity it replicates depending on its intended use. A digital shadow for assessing environmental performance for example would only need to include functionality for predicting environmental metrics. Most of the static and dynamic data layers (or the technologies required to create them) that would be necessary for constructing a digital farm shadow for environmental performance are available. Spatial soil maps, ongoing climate monitoring, soil status monitoring, spatial input mapping (fertiliser, irrigation, sprays) can all be streamed from monitoring equipment to a data cloud. These data could be used to configure a digital shadow of specific farm systems and to update its status as time progresses. The model(s) that represent the shadow could then be used to interpolate farm state measurements into predictions of farm outputs or state variables that are not practical to measure. There is currently no single model that covers the full range of environmental performance metrics, but it is technically feasible to combine farm activity recording, greenhouse gas accounting, solute and sediment loss estimations and ecosystem service evaluations into an aggregated system to provide a digital shadow.

Further comparative details of the Overseer, SPASMO and APSIM models are provided in Appendix 1 to this report in Excel file format ‘C0033731 Report APPENDIX 1_Comparison of Overseer & SPASMO & APSIM models’.

3.2 Completed and current research on measuring and modelling of environmental performance of horticulture systems in New Zealand

Previous projects on the environmental performance of horticultural land uses covered a wide range of areas discussed in Section 2.1. These relevant projects are listed according to the environmental area of interest. Additional details for these projects are provided in Appendix 2 to this report in Excel file format “C0033731 Report APPENDIX 2_List of complete and current research on measuring & modelling environmental performance of horticulture land uses”.

3.2.1 Water quantity and quality

Research programmes on water quantity and quality include both modelling and other types of research (e.g. measuring, review, questionnaire, semi-quantitative analysis). SPASMO, Overseer, and APSIM are the most widely used models in New Zealand horticultural systems. The relevant modelling and measuring studies are listed below, separately, according to the models used.

3.2.2 SPASMO

SPASMO has been used for multiple modelling studies across New Zealand, in a diverse range of crops, tackling several environment related challenges. These include the proposed Ruataniwha Water Storage Scheme (central Hawke's Bay), irrigation in Manawatu, and the Waimea Dam (Nelson-Tasman). It has been used to model both water quantity and water quality issues. These include, but are not limited to, the reports/projects listed here (see Appendix 2 for further details):

- The SPASMO-IR tool to determine reasonable water use for the Bay of Plenty region.
- SPASMO modelling of water and nutrients using a GIS framework to estimate catchment loads.
- Expansion of SPASMO for determining reasonable water use for irrigation throughout the Wanganui-Manawatu region. Research report commissioned by HortResearch and the Manawatu-Wanganui Regional Council.
- Water footprint of apples. Pipfruit NZ.
- Water and nutrient leaching in the Ruataniwha Basin. Hawke's Bay Regional Council.
- Nutrient leaching under vineyards. Marlborough District Council & NZ Winegrowers.
- Te Raranga Matauranga — incorporating a SPASMO model. Objective 2. Decision support tool: Integration of HortResearch soil and water science with organic crop growing. Activity Report 30 April 2005.
- Water, Nutrients and Carbon dynamics in orchard soils.
- Modelling the Source and Fate of Nitrate Nitrogen Losses from Waimea Plains Land Uses.
- Land Management Practices and Nutrient Losses from Farms on the Poverty Bay Flats.
- Modelling Water Restrictions and Nutrient Losses for Horticulture in the TANK Catchment – An Economic Analysis.
- Waimea plains: a freshwater quantity management case study.
- Crop Production, Profit and Nutrient Losses in relation to Irrigation Water Allocation and Reliability - Waimea Plains, Tasman District.
- Modelling pesticide leaching in horticulture.
- CCA leaching from vineyard posts.
- Nutrient leaching in the Poverty Bay.

3.2.3 Overseer

Similarly, Overseer has been used to address challenges mainly around water quality in New Zealand horticultural land uses, though it can also be used to assess other issues such as water quantity, GHG emissions, and environmental impact of management strategies. It has also been applied across several regions including Hawke's Bay, Waikato and Canterbury. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Hawke's Bay Horticultural Nutrient and Financial Benchmarking Results.
- Nutrient Performance and Financial Analysis of Horticultural Systems in the Horizons Region.
- Nutrient Performance and Financial Analysis of Lower Waikato Horticulture Growers.
- Nutrient Performance and Financial Analysis of Horticultural Systems in the Waimea Catchment.
- Improving and refining estimates of nitrogen leaching for the New Zealand agricultural greenhouse gas inventory.
- Assessment of the irrigation Good Management Practice modelling proxies proposed by Irrigation New Zealand for the Matrix of Good Management (PC5).
- Arable and horticultural crop modelling for the Matrix of Good Management — a technical summary.

3.2.4 APSIM

To a limited extent, APSIM has been applied to the assessment of environmental performance of annual horticultural systems in New Zealand. This can be attributed in part to the distinctive characteristics and management practices of perennial horticultural systems, which often necessitate customised model adaptations. Additionally, the limited availability of vegetable modules restricts its application in vegetable crops commonly included in rotation systems. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Outcomes from four modelling studies exploring different irrigation strategies at six sites across New Zealand.
- Waimea Plains nitrate issues – science summary 2020 (In this project, various models such as SPASMO, APSIM, and Overseer for modelling nitrate leaching are discussed).

3.2.5 Non-model based studies

There are also some projects on water quantity and quality which are based on literature review, questionnaire survey, measurement and semi-quantitative analysis. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Water availability and security in Aotearoa New Zealand-Supporting the sustainability, productivity, and resilience of the food and fibre sector.
- Water availability and security: National-scale assessment.

- Water Availability and Security: Sensitivity Analysis.
- National water use report 2021: Questionnaire reporting, benchmarking and tracking-season 2020/21.
- What's coming out of tile drains?
- Review of nitrous oxide emission factors and activity data for crops.

3.2.6 Soil health and soil quality

In New Zealand horticulture, soil health and soil quality mainly focuses on nutrient management particularly in vegetables, but relatively less on soil physical and biological quality. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Nutrient Management Science — State of Knowledge, Use and Uptake in New Zealand.
- Fertigation — A new tool for nutrient management?
- Future Proofing Vegetable Production.
- Mineralisable nitrogen to improve on-farm nitrogen management.
- Feasibility of organic no tillage commercial vegetable production systems in the Manawatu.
- Vegetable production nitrogen management workshops.
- Best practice management of nitrates in process cropping.
- Proof of concept for a Novel biostimulant/biofertiliser formulation.

3.2.7 Biodiversity

Relevant projects mainly focus on exotic plant species, the benefit of introducing diversity into crop systems. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Taking stock: Resolving New Zealand's cultivated plants problem.
- Daffodil Galanthamine project.
- Sauvignon Blanc Grapevine Improvement Programme.
- Biodiversity for beneficial insects; delivering benefits to growers from designed native plantings.

3.2.8 Greenhouse gas emissions

These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Purity of agricultural lime and dolomite (GHGIR 2021/22).

- N_2O emission factors for fertilisers (GHGIR 2021/22).
- Development of an autonomous low emissions tractor for trellised orchard systems.
- Evaluation of process-based models for predicting N_2O emissions — final report.

3.2.9 Climate change

Sustainable Land Management and Climate Change (SLMACC) has funded a range of projects on climate change and associated adaptations and mitigations, such as impacts of adverse events, pest and disease management, erosion control, biosecurity and so on. Usually models for both climate and environmental performance (e.g. disease risk, erosion models) are integrated. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Analysis of potential climate change impacts on horticulture's spatial footprint (Sustainable Land Management and Climate Change 2017/18).
- Quantifying climate change adaptation plans (SLMACC Adaptation 2020/21).
- Economic impacts of adverse events (SLMACC Adaptation 2020/21).
- Participatory pathways for primary industries (SLMACC Adaptation 2020/21).
- Disease response to climate change (Sustainable Land Management and Climate Change 2011/12).
- Erosion and erosion control review (Sustainable Land Management and Climate Change 2011/12).
- Advanced weather and climate modelling of vineyard regions (Sustainable Land Management and Climate Change 2012/13).
- Effects of climate change on current and potential biosecurity pests and diseases in New Zealand (Sustainable Land Management and Climate Change 2013/14).
- Climate change: trade and biosecurity (SLMACC Adaptation 2020/21).
- Evaluation of profitability and future potential for low emission productive uses of land that is currently used for livestock.

3.2.10 Weed, pest and disease management

In New Zealand's horticulture sector, a lot of efforts have been put to manage weed, pest and disease in a more sustainable way by reducing agrichemical use and adopting biotechnology. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Onion Pathways: Sustainable onion production system.
- AT — Network technology to optimise readiness, response and eradication of bio-security incursions in the primary sector.
- Envisi Field Trials.

- A unified approach to vegetable on-farm biosecurity.
- Meeting the demand for NZ extra virgin olive oil.
- Organic sector strategy.
- Innovating for a sustainable future.
- A scoping study of x-ray technology as a potential phytosanitary treatment for New Zealand fresh produce exports.
- Phosphine treatment of avocados..
- Food safety to meet challenging markets
- Sustainable vineyard floor project.
- Electric horticulture sprayer.
- Botrytis disease management in tunnel house blueberries.
- Precision weeding with a Smart Waterjet Weeder, not chemicals or cultivation.
- Smart and Sustainable.
- Ensuring PremA17/Smitten® reaches its full potential.
- The good bugs — enhancing pollination and natural enemies in New Zealand.
- A Lighter Touch.

3.2.11 Mahinga kai

Studies have been carried out to enhance the productivity of horticultural systems. Some of these projects are directly relevant to Māori whānau and some projects have been carried out by combining Mātauranga Māori and western science. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Aspirations of Māori Land Owners (SLMACC Adaptation 2020/21).
- Feasibility of growing hi-oleic peanuts in Northland.
- Redefining great food: more plants on more plates for more people (and a better planet).
- Vineyard-scale monitoring of unproductive vines.
- Orchard digital twin system for orchard optimization.
- Creating best practice guidelines to reduce kiwifruit losses.
- Growing an almond opportunity! Feasibility of a New Zealand almond industry.
- Feasibility of growing hi-oleic peanuts on a commercial scale in Northland.

- Future Orchard Planting Systems.
- Peria Horticultural Programme.
- Karioi – reconnecting our whānau to their whenua.
- Understanding the opportunity for avocados in Northland.
- Miro –Transforming Māori land to high-value horticulture.

3.2.12 Others

Previous projects also covered other environmental targets such as waste management, greenhouse industries, plasticulture and recycling. In addition, regenerative agriculture practices are also applied to assess the whole systems including soil health, water quality, greenhouses gas emissions, production, profitability, human wellbeing etc. These include, but are not limited to the reports/projects listed here (see Appendix 2 for further details):

- Beyond Carbon Zero.
- Feasibility study of the economic validity of nutrient extraction from non-commercial grade potatoes and kumara.
- Multi-region pilot testing of urban farm growing of 'out of season' spray free strawberries.
- Sustainable produce farming.
- Biodegradable plastic pots incorporating NZ ingredients.
- RF – Regenerative management systems for New Zealand vegetable production.
- RegenHort – Boosting NZ horticulture through regenerative practices (Stage 1 - Opportunity Discovery).
- Carbon Positive – Regenerating soil carbon in soils used for intensive field cropping.
- Regenerative management systems for New Zealand vegetable production.
- Feasibility of mulch-direct planting and minimum till cultivation in commercial vegetable production systems in the Manawatu.

3.3 Methodologies for assessing impacts of water shortage

Assessment of the impact of water shortage consists of three parts:

1. Quantification of the timing and extent of crop stress that results from water shortage. This is usually carried out by expressing crops demand for water relative to their supply of water from the soil.

2. Quantification of the impact of that stress on crop, yield and product quality. This may be performed by predicting the response of underlying process like photosynthesis and phenology or using simple empirical relationships between stress indices and outcomes of interest.

3. Determination of the spatial, temporal and contextual variation in stress impacts. For a given shortage scenario the impacts will depend upon the soils at a particular location (spatial), the weather conditions for a given year (temporal) and the management options applied in the given context. These variations need to be taken into account to determine where, how often and how severe the impacts of shortage will be.

3.3.1 Modelling the timing and extent of water stress

An actively growing plant loses water from its leaves as a result of maintaining its stomata open to assimilate carbon dioxide for photosynthesis. This process is called transpiration and represents the crop's demands for water. Transpiration loses are replenished with soil water extracted by roots. This represents the plant's supply of water. During water shortage the soil will dry out and supply from the roots declines to a point where it can no longer meet demand, leaf stomata will close to prevent desiccation but photosynthesis declines as a result. The greater the supply shortage and the longer it goes on for the more photosynthesis will be lost and the more potential yield will decline. As such, stress can be quantified as a ratio between water supply and demand (Brown et al. 2009).

Transpiration demand

There are a number of approaches for calculating demand but the Penman Monteith equation, as formulated by the FAO (Allen et al. 2006), is an internationally accepted standard. It takes meteorological data (air temperature, vapor pressure, wind speed and solar radiation) and estimates of crop canopy characteristics (height, stomatal conductance, albedo) to estimate what depth of water (mm) would be transpired by a hypothetical crop that is fully covering the ground and actively growing. This number is then adjusted down based on the crop's leaf area if it is not fully covering the ground. These equations are relatively simple and can be implemented in a spread sheet.

Water supply

Water moves across a pressure gradient from the soil to the roots. Water conductivity declines as the soil dries and the size of the pressure gradient from the soil to the roots decreases which reduces uptake. Rainfall and irrigation replenish the soil water which increases supply again but in water shortage this does not keep pace with transpiration losses and supply becomes limited. Supply is multidimensional as it depends on the root length density at a given depth in the profile and the horizontal and vertical extent of root penetration through the soil. The calculation of water supply usually involves the separation of the soil into layers by depth and the integration of water supply calculated daily at each depth. This requires a prediction of water extraction from each depth and the infiltration/percolation of water to and from each depth to give a daily prediction of the soil water content. While the calculations are quite simple, the logistics of dealing with multiple layers is complicated so the calculation of water supply is best carried out using a coded model.

The calculation of water supplies and demands is fundamental to crop systems models and almost all the models listed in Section 3.1 have similar approaches to calculating them. As such, this can be considered ubiquitous within different model options and determination of the appropriate models determining water stress should be based on which crops and response variable they are able to consider.

3.3.2 Quantifying the impact of stress on yield and quality

Simple empirical models

An example of such models is given by Martin et al. (1992), who measured the yield of potatoes in response to maximum soil moisture deficit. They showed yield declined from its maximum potential where no water deficit was encountered to only 20% of its potential when maximum potential water deficit of 300 mm was encountered. This model could be used to give an indication of the potential yield losses in situations of different weather and irrigation, but calibration data are required for different soil types and different management contexts.

Process models

Deterministic systems model like APSIM and SPASMO are best suited to assessing impact of water stress because they can be configured with different soils and climates to represent a range of supply and demand scenarios. They can also be parameterised for a number of crops where leaf expansion and senescence respond to daily amounts of water stress and to management interventions like leaf thinning or pruning to give dynamic predictions of water demand and water stress. The stress calculations are then used to influence predictions of production (photosynthesis) and quality (biomass partitioning and yield composition). For example, APSIM has been used to predict the water stress and irrigation responses of wheat, barley, maize, pea, kale and potato under different climate change scenarios at 4 sites in New Zealand (Brown 2004; Brown et al. 2009; Teixeira et al. 2014; Sim et al. 2017). While assessing climate change effects was the focus of that study, the same approach could be used to assess the implications of irrigation allocation or other management actions.

3.3.3 Determining variation in stress impacts

The effects of water shortage will vary considerably from year to year and site to site. It is important to understand the extent of this variability to know where and when action must be taken. For instance, if all growers in an over allocated catchment had to reduce their annual irrigation allowance to half, this would not affect everyone the same. Growers growing pasture on shallow soils for example might be affected most and substantial changes in their systems required as a result. People growing crops on deep soils might not be affected at all and other land uses on intermediate soils might be affected in dry years but not in wetter years. It is important to be able to quantify this variation so effective planning can be conducted when designing policy and in determining how individual growers will be affected and need to respond to that policy. Deterministic systems models like APSIM and SPASMO are well suited to contributing to this task as simulations can be set up for as many combinations of climate, soil and management as necessary.

3.4 Conclusions

- The use of models to assess environmental performance in horticulture systems is discussed in this section. Simple models can be used to record grower activities and farm system characteristics to assess potential benefits or harm to the environment, but they may not provide a clear picture of overall environmental performance. More detailed approaches involve quantifying farm outputs through existing or additional data collection and using models to predict outputs that are not practical to measure in non-research contexts. Seven categories of models can be classified. They are farm scale accounting models, basic farm models, deterministic farm system models, single crop decision support systems, detailed process models, catchment erosion/sediment models, and digital farm shadow. Each category has its own characteristics, and the accessibility of the models depends on the expertise of the operator. It is important to have skilled operators to ensure that input data and configurations are defensible and that the results produced are valid.

- ProductionWise is a farm record management system that estimates greenhouse gas emissions by applying emissions factors to inputs such as crop types, yields, fuel consumption, and fertiliser use. It does not consider soil carbon changes due to cultivation and crop type, and N_2O losses vary based on environmental conditions. Other similar models include Cool Farm Tool for greenhouse gas emissions, water footprint, and biodiversity scores, and simple spreadsheets by HortNZ and MfE for N_2O and CO_2 emissions from fertiliser and lime/dolomite application.

- Overseer is a farm simulation model used to model the nitrogen, carbon, and water balances of different farm types in New Zealand. It takes inputs of climate, soil, and management practices to predict nutrient losses, greenhouse gas emissions, and water balance variables. Overseer is available through subscription and has been criticised for its lack of confidence in predicting nitrogen loss to waterways. No other similar models have been identified for horticultural crops.

- APSIM is a widely used deterministic farm systems model that predicts nitrogen leaching, denitrification, and soil carbon losses/sequestration. While extensively adopted in agricultural crop modelling, its application in horticulture has been more constrained. It has a flexible approach to specifying management and making custom calculations during runtime. Inputs required include climate, soil, and management information. Outputs include irrigation and fertiliser applications, drainage, runoff, leaching, soil moisture content, crop nitrogen uptake, transpiration, evaporation, denitrification, mineralisation, soil carbon, and soil nitrogen. APSIM is under continuous development and freely available for research purposes. Other similar models include SPASMO, DSSAT, STICS, CropSyst, and AquaCrop.

- Single crop decision support tools, such as the Potato Calculator developed for sustainable potato production, have inputs and outputs similar to deterministic farm system models. These generally have web-based user interface to simplify configuration and updating of information for the crop fields, providing forecasts for irrigation and fertiliser requirements, and postharvest analysis for future improvements. Other examples of such systems include the Wheat Calculator, AmaizeN, AquaTrac, SVS Vegetable nutrient management tool, Irrigation-allocation calculators, Pesticide Risk Calculator, and Crop Calculator for water use in UAE.

- Hydrus is a detailed process model for water flow and solute transport in soils. It requires expert users, substantial parameterisation information, and is slow to execute, so it may not be suitable for estimating environmental effects on-farm. Other examples of detailed process models include DNDC for predicting trace gas emissions and GroIMP for modelling plant growth.

- A digital farm shadow is a virtual representation of a physical entity that can be used to predict environmental metrics by combining farm activity recording, greenhouse gas accounting, solute and sediment loss estimations, and ecosystem service evaluations. Although no working examples of digital shadows of agricultural systems exist in New Zealand, it is technically feasible to create one by streaming data from monitoring equipment to a data cloud and configuring a model that represents the shadow.

- We discussed completed and current research on measuring and modelling the environmental performance of horticulture systems in New Zealand, specifically focusing on water quantity and quality. SPASMO, Overseer, and APSIM are the most widely used models in New Zealand horticultural systems for modelling studies. They are mainly used to address challenges around water quantity (e.g. water use, irrigation) and quality (e.g. nutrient losses, nitrate leaching), GHG (e.g. N_2O) emissions, and environmental impact of management strategies.

- In New Zealand horticulture, soil health and soil quality mainly focuses on nutrient management particularly in vegetables, but relatively less on soil physical and biological quality. Relevant projects mainly focus on exotic plant species and the benefit of introducing diversity into crop systems. Reports and projects related to greenhouse gas emissions focus on evaluating the purity of agricultural lime and dolomite, N_2O emission factors for fertilisers, N_2O emission factors and activity data for crops, development of an autonomous low emissions tractor for trellised orchard systems, and evaluating process-based models for predicting N_2O emissions. Sustainable Land Management and Climate Change (SLMACC) has funded a range of projects on climate change and associated adaptations and mitigations, such as impacts of adverse events, pest and disease management, erosion control, biosecurity, and so on.

- Efforts have been made in the New Zealand horticulture sector to manage weed, pest and disease in a more sustainable way, through reducing agrichemical use and adopting biotechnology. Projects have been carried out to enhance productivity of horticultural systems, combining Mātauranga Māori and western science, which are relevant to Māori whānau. Other projects have covered waste management, greenhouse industries, plasticulture, recycling, and regenerative agriculture practices to assess whole systems including soil health, water quality, greenhouse gas emissions, production, profitability, and human wellbeing.

- Assessing the effects of water shortage on crops involves three parts: quantifying crop stress resulting from water shortage, quantifying the impact of stress on crop yield and product quality, and determining spatial, temporal, and contextual variation in stress effects. Quantifying stress involves calculating the ratio between water supply and demand, which can be performed using the Penman Monteith equation. Water supply depends on root length density and the extent of root penetration and is best calculated using a coded model. Crop systems models use similar approaches to calculate water supplies and demands, and the appropriate model to use should be based on the crops and response variables being considered.

- Empirical and process models can be used to quantify the effect of water stress on crop yield and quality. Empirical models provide simple estimations, while process models like APSIM and SPASMO offer more precise predictions based on different soils and climates. The variability of stress impact across different locations and years must also be taken into account, and deterministic systems models can help in designing policies and determining individual grower responses.

4 Glossary

Alpha diversity: the diversity within a single ecosystem or habitat, and it is often quantified as the number of species present in a particular area or sample.

Attributes: characteristics or features that describe a particular object or entity, such as a given environmental metric.

Biodiversity: the variety of life on Earth, including the genetic, species, and ecological diversity of all organisms, from microorganisms to plants and animals.

Biodiversity footprint: a measure of the impact of human activities on biodiversity, which refers to the variety of living organisms in a given area or ecosystem. It is a way of quantifying the extent to which human activities are contributing to the loss of biodiversity and the degradation of natural habitats.

Carbon footprint (CF): a measure of the total amount of greenhouse gases (GHG), especially carbon dioxide (CO_2), emitted by an individual, organisation, event, or product. It is usually measured in terms of the amount of CO_2 equivalent (CO_2e) emitted, which takes into account the global warming potential of other GHGs like methane and nitrous oxide.

Chemical footprint: a measure of the total amount of harmful chemicals used in the production, distribution, and disposal of a product or service. It includes all types of chemicals, such as those used in manufacturing, cleaning, and packaging, as well as those released into the environment as a result of the product's use and disposal.

Circular economy: an economic system that aims to keep resources in use for as long as possible, extracting maximum value from them, and minimizing waste and pollution.

Conventional full irrigation: a method of crop irrigation that involves applying enough water to completely saturate the root zone of the plants. In this method, water is often applied uniformly across the entire field using sprinklers, furrow irrigation, or flood irrigation. This approach aims to ensure that plants receive the maximum amount of water they need to grow and produce yields, although it may also result in higher water usage and lower water use efficiency compared to alternative irrigation methods.

Crop factor: a dimensionless factor that represents the water use or evapotranspiration rate of a specific crop relative to the reference evapotranspiration (ET_0) of a standardized grass or vegetation cover, under the same climatic conditions (also known as crop coefficient).

Data envelopment analysis (DEA): a method used in operations research and management science to evaluate the efficiency of decision-making units (DMUs).

Eco-efficiency: the ability of a product, process, or service to deliver environmental benefits while minimising resource use and costs. It involves the integration of environmental and economic considerations in the design, production, and consumption of goods and services.

Ecological footprint: the aggregate area of land and water in various ecological categories that is claimed by participants in that economy to produce all resources they consume, and to absorb all their wastes they generate on a continuous basis, using prevailing technology.

Ecosystem services: the benefits that people derive from natural ecosystems, including provisioning, regulating, cultural and supporting services.

Energy footprint: a measure of the total amount of energy used in the production, distribution, and disposal of a product or service. Energy is a concept that includes all forms of energy and resources that have been used to create a product or service, including renewable and non-renewable resources. It is based on the idea that all forms of energy and resources have an inherent value and can be converted into a common unit of measure. The energy footprint can be calculated using different indicators, such as the total energy consumed, the energy intensity of the production process, or the environmental impact associated with energy use.

Energy footprint: a measure of the total amount of energy used in the production, distribution, and disposal of a product or service. It includes all types of energy, such as electricity, fossil fuels, and renewable energy sources. The energy footprint can be calculated using different indicators, such as the total energy consumed, the energy intensity of the production process, or the carbon emissions associated with energy use.

Energy productivity: a measure of how efficiently energy is used to produce goods or services. It is calculated by dividing the output or value of goods or services produced by a system, organisation, or economy by the amount of energy input required to produce them.

Energy use efficiency: the measure of how effectively energy is converted into useful work or services. It is calculated by dividing the amount of useful energy produced or delivered by a system, device, or process by the total amount of energy inputted.

Environmental impacts: the actual effects that a particular activity or process has on the environment.

Environmental metrics: quantitative measurements used to evaluate the environmental performance of an organisation, process, product, or service. Examples of environmental metrics include greenhouse gas emissions, water consumption, waste generation, and energy use.

Environmental performance: how well an organisation or individual is managing its environmental impact to ensure sustainable use of natural resources.

Evapotranspiration: the combined process of water vapor evaporation from soil and plant surfaces and transpiration of water from plant tissues to the atmosphere.

Footprints: the impact that human activities have on the natural environment. It is generally expressed as a 'cost' (say L of water or kg of CO_2) divided by a ‘benefit’ (kg of fruit, or L of wine).

Gamma diversity: the diversity across multiple ecosystems or habitats, and it is the total number of species in a given geographic region.

Global warming potential (GWP): a measure of the relative ability of a greenhouse gas (GHG) to trap heat in the atmosphere compared to carbon dioxide (CO_2) over a specified time period, usually 100 years. It is used to estimate the total impact of all GHG emissions on the Earth's climate over a given time period.

Harvest index: a measure of the efficiency of a crop in converting the photosynthetic energy it receives into harvestable yield, expressed as the ratio of the economic yield (e.g. edible or marketable portion of the crop) to the total plant biomass.

Heavy metal: a group of elements that have a high density and atomic weight. Some examples of heavy metals include lead, mercury, cadmium, arsenic, and chromium. While some heavy metals are necessary for human health in small amounts (e.g. iron, zinc, and copper), excessive exposure to many heavy metals can be toxic and cause serious health problems.

Hot water extractable carbon (HWEC): a measure of the amount of organic carbon that can be extracted from soil using hot water. This method is often used as an indicator of the labile, or easily decomposable, carbon pool in soil, which is important for understanding nutrient cycling and overall soil health.

Hot water extractable organic nitrogen (HWEON): a measure of the amount of nitrogen that is extracted from soil or other organic matter using hot water. It is a commonly used method for assessing the labile or easily available nitrogen in soil, which can be taken up by plants or lost through leaching.

Integrated Pest Management (IPM): a sustainable and ecologically-based approach to managing pests in agriculture, forestry, and other ecosystems. It involves the coordinated use of multiple techniques, including cultural, physical, biological, and chemical controls, to suppress pest populations and prevent economic damage, while minimizing risks to human health and the environment.

Irrigation water productivity: a measure of the amount of crop yield produced per unit of water applied through irrigation. It specifically focuses on the efficiency of water use in irrigated agriculture systems.

Key performance indicators (KPIs): measures of an organisation's overall performance against its strategic objectives. KPIs might include financial metrics such as revenue, profit margins, or return on investment, as well as operational metrics such as customer satisfaction, employee engagement, or productivity. KPIs are used to monitor an organisation's performance over time, and to identify areas where improvements are needed to achieve its strategic goals.

Land footprint: a measure of the amount of land that is used to support a particular activity, product, or service. It is usually expressed in terms of the area of land required to produce the resources or support the activities associated with the product or service.

Life Cycle Assessment (LCA): a comprehensive methodology used to evaluate the environmental impact of a product or process throughout its entire life cycle, from raw material extraction to disposal or recycling. It is a systematic and objective approach to assess the environmental aspects and potential impacts of a product, process or service.

Mahinga kai: a Māori concept that refers to the customary management and use of natural resources for food, materials, medicine, and spiritual well-being. It includes practices such as hunting, fishing, gathering, and cultivation, as well as the associated cultural and social customs and values.

Material footprint: a measure of the total amount of natural resources, such as minerals, metals, and biomass, which are used to produce a product or service. It includes all stages of the product life cycle, from extraction of raw materials, through processing, manufacturing, distribution, use, and disposal.

Maximum Contaminant Level (MCL): the maximum allowable level of a contaminant that is permitted in drinking water as established by the United States Environmental Protection Agency.

Maximum residue level (MRL): the maximum amount of pesticide residues or veterinary drugs that can remain in or on food products when they are sold to consumers.

Nitrate leaching: the process by which excess nitrates from fertilisers or other sources move through the soil into groundwater or surface water.

Nitrogen footprint: a measure of the total amount of reactive nitrogen (Nr) released to the environment as a result of human activities, including food production, transportation, and energy use. It is usually expressed in terms of the amount of nitrogen released per person, per organisation, or per product.

Nitrogen use efficiency: a measure of how effectively plants utilise nitrogen from soil or fertiliser to produce biomass. NUE is typically calculated as the ratio of the amount of nitrogen taken up by the plant to the total amount of nitrogen applied to the soil or added through fertiliser.

Nutrient use efficiency: the amount of nutrients taken up by a plant and converted into biomass or yield relative to the amount of nutrients applied or available in the soil.

Partial Root Zone Drying: an irrigation technique for plants that involves alternating the irrigation of different sections or halves of a plant's root zone.

Phosphorus footprint: a measure of the total amount of phosphorus used in the production of a product or service, including all stages of the product life cycle from extraction of raw materials, through processing, manufacturing, distribution, use, and disposal.

Plant water use efficiency: a measure of the amount of biomass produced by a plant per unit of water transpired, or the ratio of the rate of photosynthesis to the rate of transpiration.

Quick N Test: a rapid soil testing method used to determine the concentration of plant-available nitrogen (N) in the soil.

Regenerative agriculture: a holistic approach to farming that aims to enhance and sustain the health of the soil, the environment, and the community.

Risk matrices: tools used to assess and prioritise risks in a project or organisation, which are visual representations that help identify and evaluate the likelihood and impact of different types of risks.

Soil compaction: the process by which soil particles are pressed together and the pore spaces between them are reduced in size.

Soil health: the ability of soil to function as a living ecosystem that sustains plants, animals, and humans.

Soil quality: a broader term that refers to the overall condition of the soil in terms of its physical, chemical, and biological properties. Soil health is a component of soil quality, but it focuses specifically on the soil's ability to support living systems and ecosystem functions.

Specific energy: the amount of energy required to perform a particular task or produce a specific output per unit of mass or volume of a substance. It is commonly measured in units of energy per unit of mass, such as joules per kilogram (J/kg), or energy per unit of volume, such as joules per cubic meter (J/m^3).

Spray efficiency: the effectiveness of a pesticide application in terms of the proportion of the spray material that reaches the target area or target pest.

Spray retention: the amount of pesticide solution that is deposited on the target surface (such as plant foliage) and remains on the surface without being lost due to runoff, evaporation, or other factors.

Tikanga Māori: the customs, values, protocols, practices, and worldviews of the indigenous Māori people of Aotearoa New Zealand. It encompasses the traditional knowledge and practices that have been passed down through generations and is an integral part of Māori culture and identity.

Toxic metals: heavy metals that can cause harm to human health even at low levels of exposure. These include lead, mercury, cadmium, arsenic, and others. Exposure to toxic metals can occur through contaminated food or water, occupational exposure, or exposure to environmental pollutants. Toxic metals can accumulate in the body over time and cause a range of health problems, including neurological damage, organ damage, and cancer.

Water footprint: a measure of the total amount of water used directly or indirectly by an individual, organisation, or product. It includes both the amount of water used in the production or processing of goods and services, as well as the water used in the consumption or use of those goods and services. It usually includes three components: green, blue and grey water footprints.

Water productivity: amount of economic output or yield produced per unit of water used. It is calculated as the ratio of the economic benefit (e.g. crop yield, revenue) to the volume of water consumed, withdrawn, or depleted in the production process.

Water quantity: the amount of water available in a particular location or region. It can be measured in various units such as volume, mass, or flow rate, and is typically expressed in terms of a specific time period (e.g. litres per second, cubic meters per day, etc.). Water quantity is an important factor in determining the availability of water for various uses, such as agriculture, industry, and domestic consumption.

Water supply reliability: the ability of a water system to consistently provide an adequate quantity and quality of water to meet the needs of its users over a specified period of time, typically years or decades.

Water use efficiency: a measure of how effectively plants use water to produce biomass. It is typically calculated as the ratio of the amount of biomass produced to the amount of water used by the plant.

Water use: amount of water consumed, withdrawn, or diverted from a water source for a specific purpose (e.g. crop growth).

5 Acknowledgements

We would like to express our appreciation to our colleagues Melanie Davidson, Weiwen Qiu, Soonie Chng, Mike Cummins, Roberta Gentile, and Grace Xu for contributing a previous review work (cited as: Hu W, Davidson M, Qiu W, Chng S, Cummins M, Gentile R, Xu G 2022. Environmental impacts of apple production: A review) that has been extensively cited in the report. We also thank Jacqui Todd, Soonie Chng, Jenny Green, and Weiwen Qiu for providing comments that further improved this report. The authors thank the Science Publication Office for editing and formatting support, and Penny Tricker and Miriam Hall for helpful comments and suggestions provided as part of the formal review process at The New Zealand Institute for Plant and Food Research Limited.

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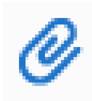
Appendices

Attached to this PDF: 23816-C Report APPENDIX 1.xlsx.

Attached to this PDF: 23816-C Report APPENDIX 2.xlsx.

To open Excel file attachments:



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