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Mitigation options to reduce nutrient loss in the Otago Region

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Executive summary

Mitigation options to reduce nutrient loss in the Otago Region

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January 2023

Loss of nutrients, especially nitrate-nitrogen (NO_3^--N) and phosphate (P), from farmland to surface and ground water can reduce farm productivity, harm the environment, and, in the case of NO_3^--N, affect drinking water quality. Effective nutrient management on farms is therefore a priority for both farmers and regional authorities. Recognising this, and in response to the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020), regional authorities across New Zealand are developing regional plans to improve water quality. To this end, Otago Regional Council (ORC), engaged The New Zealand Institute for Plant and Food Research Limited (Plant & Food Research) to prepare a report on mitigation strategies for reducing nutrient losses in the Otago region. The aim was to increase understanding of the range of mitigation options available to reduce nutrient losses from land to water in the arable and horticultural farming systems practiced in the region. The main objectives were to categorise options into Good Management Practices (GMPs), for activities that are already being or will be implemented on farms over the next 2–5 years or Good Management Practices Plus (GMP+) for activities that are more difficult or expensive or take longer time frames to implement. These would then be quantified in terms of effectiveness and costs (low, moderate, and high).

The report is based on the data retrieved from searches as a mix of white (reviewed scientific papers) and grey (generally technical reports) literature. Additional sources of information were from Plant & Food Research and/or industry experts with knowledge on N leaching and P runoff from arable and horticultural [vegetable and tree] crops. The report is based on crop types, and districts or territorial authority areas where the different crops are grown. There are five districts in the Otago Region, namely Clutha, Dunedin City, Queenstown Lakes, Central Otago and Waitaki. The distribution of the different crops [cereals, vegetable, or fruit trees] varied with district, and depending on weather conditions. Our review showed that more than 90% of the summerfruit and pipfruit are grown in Central Otago, while ≥ 80% of the cereals are grown in Clutha and Waitaki districts. All the vegetable crops are grown in Waitaki and Dunedin districts, except for carrots for which ~96% are grown in Clutha.

Availability of literature on mitigation options on NO_3^--N leaching varied with farming sector: arable > vegetables > fruit trees, while there was very little to no literature on P loss. Very few of these reports were specific to the Otago region, and therefore most of the discussions are extrapolated from other regions in New Zealand or overseas. Furthermore, most of the literature on fertiliser use or NO_3^--N leaching is dated, and therefore caution should be applied when interpreting the data reported here. Across the sectors, leaching losses were mainly associated with environmental factors [e.g. weather and soil factors] and management practices, e.g. fertilisers, and cultivation. As most of the NO_3^--N leaching in arable cropping systems was from soil organic matter (SOM) that is mineralised between

harvest and the start of winter, the length of the fallow period and the amount of N uptake by the following crop is important. Therefore, the growing of cover/catch crops over the winter period or reducing the length of the fallow period would be the best technologies for reducing winter NO_3^- -N leaching losses in these sectors. Across the sectors, low-cost, and moderately effective, technology GMPs include fertiliser management, irrigation scheduling/moisture sensing, fertigation, and residue management, while low-cost, highly effective technologies include soil/plant testing and use of decision-support tools. The GMP+ were identified for the high-value vegetable crops only, and included the use of soilless/hydroponic growing, and vertical farming, as well as irrigation design.

Key findings

1. There is very limited information on NO_3^- -N leaching and P loss across the sectors for the Otago region. The few available reports on N fertilisers are dated.
2. However, data are available for other regions in New Zealand: vegetables in Pukekohe and Canterbury, fruit trees in Nelson/Marlborough, Wairarapa, and the Bay of Plenty, and arable (cereals) in Canterbury. Extrapolation from these data is made complicated because of different climate and soils.
3. Because of the lack of information on most of these crops/trees, it was very difficult to estimate NO_3^- -N leaching.
4. Most of the technologies discussed, especially for the GMP, are applicable across the sectors; however, those that are for the GMP+ are suitable for the high-value crops, and in all cases for the vegetable crops. High-cost technologies tended to have high potential for mitigating NO_3^- -N leaching.
5. Most of these technologies are already available in New Zealand, in some form.
6. The effectiveness of some of these technologies will depend on specific environmental conditions (e.g. weather and soil), and the crop/crop rotation factors.

Recommendations

7. That a comprehensive farmer survey be carried out in the Otago region on management of arable/vegetable/fruit trees, in relation to irrigation and fertiliser management. This will either confirm the result of the report or allow for further refinement.
8. Address the large gap between our understanding of barriers and adoption of mitigation approaches
9. Undertake whole-system modelling approaches to understand the opportunities for technologies to mitigate NO_3^- -N leaching using process-based system models.

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1 Introduction

There is increasing pressure on New Zealand’s farming sectors to better utilise nutrients to improve environmental outcomes including water quality and climate change mitigation. Recent policy initiatives such as the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020) and the National Environmental Standards for Freshwater (NES-F) 2020 underline the importance of supporting the different sectors to measure and better manage on-farm nutrient losses. This report covers three farming sectors [arable, vegetable and tree horticulture], and the total hectarage for each sector in the Otago region and New Zealand are shown in Table 1 (FreshFacts 2021; Gentile & McNally 2021; AIMI 2022). For the Otago region, the most common arable crops are cereals [wheat, barley, and oats], and other grain crops. There are no maize (grain or silage) crops grown in Otago, and therefore the total area reported in Table 1 excludes maize. In the horticultural sector, the most common vegetables grown are potatoes, broccoli, cabbage, cauliflower, lettuce, leafy greens [e.g. spinach, mesclun], and asparagus; while the tree horticultural sector is dominated by grapes, pipfruit [apples and pears], nuts [mainly hazelnuts and walnuts] and summerfruit [mainly apricots, cherries, nectarines, peaches, and plums]. All these fruit trees are deciduous (Uriu & Magness 1967), and normally lose all their leaves in autumn and winter. This has implications on nutrient cycling.

Nutrient applications in the three sectors are diverse, better understood for the arable sector (Jamieson et al. 1998; Armour et al. 2002; Armour et al. 2004) than for the vegetable (Michel et al. 2021) and fruit tree (Gentile & McNally 2021; Gentile et al. 2022) sectors. Furthermore, there are various mineral and organic products available either as soil-applied, foliar sprays or fertigation amendments across the sectors. Consequently, the understanding of nutrient dynamics particularly in the vegetable and perennial horticulture systems is methodologically complex owing to faster rotations in the former, and high spatial variability and perennial growth patterns in the latter, as well as the plant nutrient storage and remobilisation among the different vegetables or fruit trees.

1.1 Land use in the Otago Region for sectors under consideration

A summary of the land use in the Otago region is given in Table 1 and Appendix 1. The area of vegetables in Otago has fluctuated the most over the last two decades, being higher in the early 2000s, ranging from 600 ha to 850 ha per year, and steadily decreasing to the lower 400s ha/year between 2008 and 2012, to around 300–350 ha thereafter to today (FreshFacts 2000–2021). In contrast, the area under fruit trees has increased steadily, from ∼2000 ha in 1999 to ∼2500 ha in 2002, and 2300–3400 ha thereafter to today. Total area under cereals in New Zealand has gradually declined over the last decade, from an estimated 137,400 ha in 2010 to 120,000 in 2015, and 98,000 ha in 2020.

Table 1. Total area under cropping in New Zealand for the different sectors [arable, fruit tree and vegetable] production in 2021 (FreshFacts 2021; AIMI 2022). See Appendix 1 for more details.

Regions	Farming sector (ha)		
	Arable	**Fruit tree Horticulture**	**Vegetable Horticulture**
Otago Region	7510	3010	425
New Zealand (total)	95000	68000	45200

1.2 Otago climate

Otago is in the southern half of the South Island of New Zealand and its climate can be broken into two broad types: the coastal climate of the coastal regions and the more continental climate of the interior. The Otago region, in particular Central Otago, has some of New Zealand's highest and lowest temperatures, and its lowest rainfall (NIWA 2022). This has influenced the type of farming practised in the different districts, with cold-tolerant crops grown in the elevated region, Central Otago. Weather data for Otago (Table 2) (NIWA 2022) and the long-term weather data are shown in Appendix 2. Central Otago is drier than the other districts.

Table 2. Long-term average rainfall (mm) and temperature (°C) details for the five districts covered by the Otago Regional Council (1981–2010) [see Appendix 2 for full details].

District	Centre	Rainfall (mm)			Temperature (°C)		
		Mean annual	Wettest month	Driest month	Average max.	Average min.	Warmest months
Clutha	Balclutha	713	Jan. (78)	Aug. (43)	15.0	8.0	Jan. (19)
Queenstown Lakes	Queenstown	750	Dec. (75)	Feb. (50)	15.0	4.0	Jan. (22)
Central Otago	Alexandra	363	Dec. (48)	July (19)	17.3	2.1	Jan. (22)
Dunedin	Musselburgh	738	Dec. (80)	Sep. (48)	14.7	6.9	Jan. (19)
Waitaki	Oamaru	551	Dec. (55)	Sep. (35)	16.0	5.0	Jan. (22)
Average		**623**	**(66.2)**	**(39)**	**(15)**	**(5.8)**	**Jan. (22)**

1.3 Summary of New Zealand available data

There are no N-leaching or P run off data specific to the Otago region, except for broccoli and potatoes (Williams & Tregurtha 2003) and apples (Goh et al. 2001; Tutua et al. 2002). These data are dated and are unlikely to be relevant as many farming practices have changed over the last 20 years. For example, changes have been reported in vegetable production systems, such as the newer fertiliser recommendations (Reid & Morton 2019) and the limited information on rates of N application from a modelling report (Anon. 2019). Furthermore, in the arable sector, new decision-support systems (DSS: an interactive [often software-based] system intended to help decision makers compile useful information … to identify and solve problems and make decisions (Shepherd & Wheeler 2010)) have been developed to guide N scheduling, e.g. Sirius Wheat Calculators (Armour et al. 2002; Armour et al. 2004). There have also been detailed analyses of NO_3^- -N leaching losses for the fruit and vegetable production systems through modelling (Green & Clothier 2009), that have highlighted the effects of soil type/depth and climate on NO_3^- -N leaching losses, particularly under different rainfall patterns.

Most of the research on vegetables has been carried out for the Pukekohe area, south of Auckland (Crush et al. 1997; Williams et al. 2000; Francis et al. 2003; Williams & Tregurtha 2003) and Canterbury (Anon. 2019). Most of the work on fruit trees has been in other regions e.g. Canterbury (Goh & Haynes 1983; Goh et al. 1995; Goh & Ridgen 1997) or on other crops, e.g. kiwifruit (Gentile et al. 2022).

Across the sectors, leaching losses were mainly associated with environmental factors [e.g. weather and soil factors] and management practices, e.g. fertilisers, and cultivation. In New Zealand cropped soils, most leaching occurs over the winter period when most of the annual drainage occurs (Thomas et al. 2011). Furthermore, fertiliser N is not the main source for N leaching, as shown by a study in winter wheat, where only 5% of the applied fertiliser (urea at 200 kg N/ha) remained in the soil at harvest and 25% of the fertiliser had been incorporated into soil organic matter (Haynes 1999). The extent of NO_3^--N leaching in arable cropping systems therefore depends on the amount of soil organic matter (SOM) that is mineralised between harvest and the start of winter, the length of the fallow period and the amount of N uptake by the following crop (Tsimba et al. 2021). The implication is that the growing of cover crops over the winter period or reducing the length of the fallow period will reduce winter leaching losses. In the arable (and vegetable) sector, the key message is to manage the amount and timing of fertiliser inputs, considering all sources of nutrients, to match plant requirements and to minimise risk of losses. Tsimba et al. (2021) reported less than 10% of the NO_3^--N leaching during the growing season, and an 85% reduction in NO_3^--N leaching under cover crops, compared with the fallow. Whole-farm NO_3^--N leaching losses in arable farms have been estimated to range from 0.5 to 34 kg N/ha across farms and seasons (Khaembah & Horrocks 2018).

Historically, high N fertiliser inputs were applied in the pre-2000 period in the vegetable sector, e.g. 150 and 400 kg N/ha in cabbages and winter spinach, respectively (Williams & Tregurtha 2003), which resulted in NO_3^--N leaching losses of 178 and 246 kg N/ha, respectively. Furthermore, Crush et al. (1997) reported N fertiliser application rates of 249 & 301 kg N/ha for summer and winter cabbages, respectively, and 370 and 430 kg N/ha for summer and winter lettuce, respectively. These resulted in NO_3^--N leaching losses of 160–360 kg N/ha. The use of high N fertiliser in vegetable crops during that period was also reported in cabbage, cauliflower or spinach crops, where 250–430 kg N/ha were applied (Francis et al. 2003), which also resulted in high NO_3^--N leaching of 70–240 kg N/ha. The NO_3^--N leaching also differed between seasons, being higher for winter than summer. This was attributed to the sparse root systems for vegetables, which are inefficient at recovering mineral N (Thomas et al. 2011) and also the slow growth due to unfavourable weather (low temperatures, and radiation receipts) in winter. For such crops the recommended practice is to split fertiliser applications to match crop demand (Williams et al. 2003) and subsequently minimise NO_3^--N leaching losses. A recent modelling report by the Agribusiness Group (Anon. 2019) for a collection of N fertiliser inputs for 10 types of vegetables grown in 12 different areas/locations in Canterbury showed that applying fertilisers to match demand resulted in low NO_3^--N leaching, of 40–60 kg N/ha, when N fertiliser was applied at 20–180 kg N/ha, under different soils with different mineral N content and under different climates.

Low N fertiliser is applied in fruit tree orchards in general (Trolove 2020, 2021), and therefore N leaching from fertilisers is low. However, the amount of NO_3^--N leaching is dependent on management of the orchard practice, whether the system is organic or conventional/integrated, and grassed-down or not (Goh et al. 2001). In apple orchards, N has been reported to be removed equally by fruit harvests and soil NO_3^--N leaching, while P was least affected by nutrient removal (Goh & Haynes 1983; Haynes 1988). The NO_3^--N leaching in these orchards was estimated at about 33 kg N/ha, against a total N input of 81 kg N/ha from fertilisers (88%) and irrigation (12%). However, in grassed-down orchards (Tutua et al. 2002), where the understorey vegetation is usually mown and therefore the plant residues are returned to the orchard floor as a source of nutrients, N returns of 513–570 kg N/ha/y and 225–310 kg N/ha/y have been reported in apple orchards at Lincoln (Canterbury) and Clyde (Central Otago), respectively. Most of the NO_3^--N leaching in orchards has been attributed to the decomposition of grass residues (Haynes & Goh 1980).

A modelling exercise in Canterbury, Tara Hills and Lincoln (Green & Clothier 2009) across different soils reported NO_3^--N leaching of 2–17 kg N/ha for a range of fruits [apples, berryfruit, grapes and summerfruit]. This region has similar rainfall (550–650 mm/y) to that of Central Otago (350–650 mm/y; Table 2, Appendix 2) where most of these fruits are grown. These figures are consistent with the 3–18 kg N/ha reported for grapes and apples in Tasman District (Fenemor & Green 2016), from another modelling exercise. Furthermore, the NO_3^--N leaching for vegetable crops was reported to be between 11 and 57 kg N/ha for the same areas in Canterbury (Green & Clothier 2009), which are also consistent with the 16–51 kg N/ha reported for the vegetables in the Tasman District (Fenemor & Green 2016).

2 Methodology

2.1 Aim

Understanding the range and potential effects of different mitigation options available to reduce nutrient losses (N and P) from land to water in arable and horticultural farming systems characteristic of the Otago region

2.1.1 Objectives

1. Identify (List) mitigation methodologies currently used to reduce N and P losses from land to water in arable and horticultural systems characteristic of the Otago region.
2. Categorise mitigation methodologies into Good Management Practices (GMP) for activities that are already being or will be implemented in farms over the next 2–5 years.
3. Categorise the mitigation methodologies into Good Management Practices Plus (GMP+) for activities that are considered more difficult or expensive or take longer time frames to implement.
4. Quantify reductions in N and P losses associated with GMP and GMP+ in term of effectiveness and costs (low, moderate, and high).

2.2 Scope

Although this report emphasises the loss of N as NO_3^- -N through leaching, P and sediment are also of interest. Phosphorus is strongly bound to soils that are high in clay and/or organic matter (McLaren & Cameron 1996), so leaching losses are lower (Trolove 2021). Therefore, the nutrient we have focused on in this report is N; however, as some of the technologies identified for mitigating N losses may also influence P and sediment, these have been noted in the report. Phosphorus and sediment losses are also important for water quality, and therefore more work should be done in this space for the sectors under consideration.

2.2.1 Literature search

We developed a list of appropriate key words and supplied them to the Knowledge Navigators within Plant & Food Research (Gee 2022), who conducted search for reports published within Plant & Food Research, and as well as relevant white and grey literature, first for the Otago region and then New Zealand and International data. This was carried out as follows:

Plant & Food Research Topic: (nutrient *OR nitrogen OR fertiliser OR soil*) AND (loss* OR reduc* OR uptake*) AND (horticultur* OR arable) AND (practice* OR manage* OR technique *OR mitigation); which was followed by more searches omitting each of the bracketed terms in turn, e.g.: without (horticultur* OR arable).

The search for the Plant & Food Research reports yielded 53 reports, but only eight were relevant to the study topic. Of these, only two reports on cereals were for Otago (Armstrong 2016b, a). There were reports for other region in New Zealand, such as Canterbury (Green & Clothier 2009), Wairarapa (Trolove 2021), Rotorua (Trolove 2020), and the Poverty Bay flats (Gentile et al. 2014).

For the published data we used:

CAB TOPIC: (practic* or mitigat*) and (effect* or cost* or economic* or reduc* or lessen) and (((nutrient* or N or nitrogen) and loss*) or runoff) and (arable* or Hortic* or vegetable* or orchard*) **13 results**

CAB TOPIC: (practic* or mitigat* or reduc* or lessen) and (effect* or cost* or economic*) and (((nutrient* or N or nitrogen) and loss*) or runoff) and (arable* or Hortic* or vegetable* or orchard*) 4710 results AND review* **279 results - 52 selected**

CAB TOPIC: (practic* or mitigat* or reduc* or lessen) and (effect* or cost* or economic*) and (((nutrient* or N or nitrogen) and loss*) or runoff) and (arable* or Hortic* or vegetable* or orchard*) 4710 results refined by: Search within topic: Cost* Or Economic*. Publication Years: 2018- 2022 **488 results - 48 selected**

Proquest noft: (practic* or mitigat* or reduc* or lessen) and (effect* or cost* r economic*) and (((nutrient* or N or nitrogen) and loss*) or runoff) and (arable* or Hortic* or vegetable* or orchard*) Applied filters (runoff OR leaching OR nitrates OR agricultural runoff OR agricultural practices OR economics OR environmental impact OR fertilizer application OR agrochemicals OR water pollution OR groundwater OR farmers OR mineralization OR nutrient loss OR vegetable growing OR denitrification OR manure OR fertilizer rates OR nutrient use efficiency) NOT (diet AND animals AND pesticides AND grasslands) **1217 results - 245 selected.**

These data were further processed, removing duplicates, and identifying several key papers of interest for further investigation. Sources included journal papers, technical/client reports and book sections/chapters, conference papers and web pages. Furthermore, we also approached other experts within Plant & Food Research to check on the completeness of the list and the efficiency of the mitigations.

2.2.2 Ranking of promising options

An extensive process was used to assess the mitigation techniques (obtained for Section 2.2.1), using a range of key criteria, such as:

1. Farming sectors (crop types).
2. Currently used or potential for application/use [GMP/GMP+].
3. Nitrate leaching reduction: absolute/relative values, or ranges reported.
4. Fertiliser management: type/rate/timing/placement.
5. Experiment types [field/modelling/questionnaires].
6. Soil types.
7. Estimated costs [GMP/GMP+].

Each technology was assessed on whether it is currently in use in Otago or other parts of New Zealand but has the potential to be used in Otago [based on farming sector or soil/weather compatibility]. The overall merits for each technique across the criteria range were determined. Ranking of different technologies was carried out through discussion with Plant & Food Research colleagues who had previously published technical reports for the various clients cited here (e.g. Trolove 2020; 2021; Michel et al. 2021; Thomas et al. 2021). This allowed the comparison of different technologies for their mitigation potentials against the estimated costs that will be incurred; these were then ranked relative to one another. A semi-quantitative approach such as used by Thomas et al. (2021) was used to rank the technologies. As there was no previous work published except for some vegetables and apples in the Otago region, the overall ranking was based on expert assessment. Reports from other regions (e.g. Trolove 2020) were used as baseline information, with careful considerations based on the comparison of soils or weather details between the regions.

The costs of implementing different technologies were based on the framework developed for commercial vegetables (Thomas et al. 2021), summarised in Table 3.

Table 3. Ranking criteria for evaluating nutrient leaching mitigation technologies for arable, and horticultural systems in New Zealand (Thomas et al. 2021).

Ranking	Mitigation effectiveness (%)	Estimated cost of implementation ($/ha)
Low	0–15	0–500
Medium	16–30	501–5,000
High	31–100	5001+

Costs are dependent on the environment and the complexity of the system. For instance, there are many options for irrigation or fertiliser management, and the selection for any given option will depend on a range of environmental and/or agronomic factors, e.g. soil type/fertility, crop type, land slope, cultivation method.

3 Results

The technologies [both GMP and GMP+] described here (Table 4) can broadly be grouped into (Thomas et al. 2021):

1. Crop-based approaches, which include catch crops, intercropping and residue management.
2. Optimising inputs, which include soil/plant testing and fertiliser management (use), irrigation scheduling and fertigation.
3. Remedial technologies, which include wetlands/riparian buffers/grass filter strips.
4. Systems optimisation, used to minimise nutrient leaching and can include preventative and remedial approaches. These include nutrient management planning, decision-support systems (DSS; Section 1.3) and precision farming techniques, irrigation design, integrated management systems and crop rotation changes.

3.1 Crop-based approaches

3.1.1 Catch crops

A catch crop is any crop that is grown with the primary objective of mopping up excess nitrogen (N) in soils, which may otherwise be lost through leaching as NO_3^--N (Fraser et al. 2013; Malcolm et al. 2022). They achieve this by their rapid uptake of residual mineral N and the reduction of the water content of soil through transpiration, which reduces the risk of drainage. Catch crops are generally grown over winter, a period of the greatest risk for NO_3^--N leaching loses; however, they should be considered for any period of fallow within crop rotations. Sowing time is critical, as a modelling study showed that the delay in sowing dates consistently reduced the average effectiveness of cover crops, from >80% for March- to <25% for June-sown crops (Teixeira et al. 2016). The key attributes of autumn or winter sown catch crops are that they are cold tolerant, winter active and have fibrous deep root systems capable of removing N at depth (Horrocks et al. 2019). The choice of catch crop varies depending on season and region, but the most used crops are cereals [e.g. barley, oats, ryecorn, triticale, or wheat] and Italian ryegrass.

Although no published work has been reported for Otago for the sectors under consideration, the principles for using catch crops are the same, so reports from other regions, e.g. Southland (Malcolm et al. 2021) or Canterbury (Malcolm et al. 2022), can be extrapolated. Catch crops are widely used in New Zealand by farmers and growers, particularly in the dairy sector (Densley et al. 2006; Malcolm et al. 2016; Malcolm et al. 2017; Chakwizira et al. 2019; Malcolm et al. 2021; Malcolm et al. 2022). However, the same principles have been applied to the arable (Tsimba et al. 2021) and vegetable (Williams & Tregurtha 2003) sectors.

Catch crops are the most widely recommended mitigation technique for field-grown crops [cereals and vegetables], as they have the greatest benefits when sown early (Teixeira et al. 2016). Furthermore, the costs are lower than for most of the other technologies, as no special machinery is required (Thomas et al. 2021). Catch crops have relatively low costs to establish, grow and harvest. Additional benefits include: (1) reduced risk of erosion and P run-off due to crop cover and reduction in soil water content; (2) improved soil quality; and (3) reduced N_2O emissions.

There are a few challenges when using catch crops, such as difficulties in sowing the crop when soils are wet (e.g. in winter) or when the period is too short to establish a crop (Teixeira et al. 2016; Malcolm et al. 2017). Another challenge may be the uncertainty around the timing and amount of N released by the soil-incorporated catch crop, which could cause farmers to err on the side of caution and apply excess N to the following crops (Thomas et al. 2021).

3.1.2 Crop rotations

Crop rotation [the practice of planting different crops sequentially on the same piece of land (Francis 2005)], is similar in principle to catch crops (Section 3.1.1). However, in crop rotations, plants of different species are used [e.g. cereals — legume rotations], and with different growth habits [e.g. rooting depth] (Thorup-Kristensen 2006). Rotations may be simple, involving two or three crops; or complex, when more crops are used. Careful crop selection and timing are needed to minimise the amount of excess N. Crop rotations should be combined with soil testing and/or fertiliser management to ensure that the subsequent crops use any residual N from the preceding crops. This is a low-cost technique, with moderate effectiveness when correctly implemented. However, other factors such as market demand may make rotations difficult to implement. Crop rotations are applicable to arable and vegetable production. It was unclear how widely this is used in vegetable production in New Zealand because of their short growing periods, but it is well defined in the arable sector.

3.1.3 Intercropping

Intercropping is the simultaneous cultivation of plant species in the same field for a considerable proportion of their growing periods (Stomph et al. 2020), ideally, growing deep- and shallow-rooting crops. It is reported to improve resource acquisition and utilisation efficiencies and improve other indicators of system performance related to sustainability. However, there are more challenges to manage, e.g. having two crops reduces the options to spray certain chemicals or to synchronise harvesting, as the two crops can mature at different dates. This is not a common technology used in New Zealand. Some of the challenges associated with crop-based approaches have been reported in Section 1.3.

This technology can be used in young orchards, when ‘economic crops’ are grown in the alley spaces of the fruit trees in the first few years or in the unoccupied spaces of the long-duration crop in the early years of tree growth (Kumar 2020). These will act as cover crops (Section 3.1.1). However, strict principles should be followed, so as not to affect the tree crops, and these include: (1) intercrops should not occupy the area where the roots of the fruit trees are concentrated; (2) soil fertility should be maintained or improved when intercrops are grown; (3) water/nutrient requirements of the intercrops should not clash with those of the main fruit trees. In orchards, vegetables are better intercrops than grain crops [which can remove excessive moisture to the detriment of fruit trees]. Furthermore, orchards can be grassed down (e.g. Goh et al. 2001). All these technologies will help in controlling the amount of N in the soils and hence reducing NO_3^--N leaching. However, a grassed-down orchard can end up having excess N when the grasses are mown and returned to the soil (Tutua et al. 2002) leading to NO_3^--N leaching (Section 1.3).

Table 4. Potential for nitrate leaching and phosphorus (P) loss reduction[1] in arable and horticulture [vegetable and fruit tree] production in New Zealand, based on effectiveness[2] of nutrient [N and P] loss reduction and cost[3] of set up.

Effectiveness	Sector/System		Costs[4,5]	
		Low (GMP)	Medium (GMP)	High (GMP+)
Low	All	Fertiliser type [**N** & P]	Nitrification inhibitors [**N**]	
	Arable		Slow-release fertilisers [**N**]	
	Fruit		Slow-release fertilisers [**N**]	
	Vegetable			
Medium	All	Fertiliser management [rates, timing & placement] [**N & P**] Irrigation scheduling & soil moisture sensing [**N** & P] Fertigation [**N**] Residue management [**N & P run-off + S**]	Constructed wetlands/riparian buffers/grass filter strip [**N & P run-off + S**] Incorporation of organic matter [**N**] Precision Ag [maps/sensors + variable rates] [**N**]	
	Arable			
	Fruit			
	Vegetable			Soilless cultivation outdoor [**N** & P]
High	All	Decision-support system (DSS) to manage nutrients and irrigation rates [**N** & P] Soil and/or plant test based [**N** & P]	Integrated farming systems [**N** & P]	
	Arable	Crop rotations [**N** & P] Catch crop/cover crops [**N** & P run-off + S]		
	Fruit	Understorey planting (grass-downs) [**N & P run-off + S**]		Irrigation design (drip irrigation) [**N** & P run-off + S]
	Vegetable	Crop rotations [**N** & P] Catch crop/cover crops [**N** & P run-off + S]		Greenhouses [soilless] [**N** & P run-off + S] Vertical farming [**N** & P run-off + S]

[1] Nitrogen [N] leaching and/or phosphorus [P] run-off and sediment [S] loss; bold font means it is main element covered by the technology.

[2] When Precision Agriculture is implemented correctly, these techniques can assure important ecosystem benefits, as the mitigation of farm pollution and reduction in resource use (Loures et al. 2020).

[3] Ranking criteria for evaluating effectiveness and cost for the different mitigation technologies are given in Table 3.

[4] GMP for activities that are already being or will be implemented in farms over the next 2–5 years.

[5] GMP+), for activities that are considered more difficult or expensive or take longer time frames to implement.

3.1.4 Residue management

This applies across the sectors under discussion, as arable and vegetable crops leave residues after harvest that contain moderate to high amounts of N (Francis et al. 2003), which risk NO_3^--N leaching as they decompose. Residue management is also important in tree horticulture, especially the grassed-down orchards (Tutua et al. 2002), reported to return 225–570 kg N/ha/y (Section 1.3). As fruit trees have low N demand, most of this N will be exposed to leaching under high drainage. However, this technique addresses only one source of NO_3^--N leaching, crop residues, but not the high N soils or over-fertilisation.

Residue management includes leaving the residues undisturbed, rather than incorporating them into the soil (Thomas et al. 2021). This could also help in reducing P and sediment run-off. Alternately, residues can be removed and used as compost. However, this exports residues and nutrients into other area, resulting in soil degradation, as residues are important in retaining soil structure. Residue management needs to be part of the nutrient management plan. Overall, this is a low-cost, moderately effective technique.

3.2 Optimising inputs

Techniques include irrigation scheduling (Quemada et al. 2013), fertigation (Incrocci et al. 2017), soil testing (Curtin et al. 2017) and plant tissue testing (Fageria 2003), and fertiliser management (Williams et al. 2003).

3.2.1 Irrigation scheduling

This applies to irrigated crops only, and across the three sectors. Previous studies on management practices that adjust water application to crop needs showed reduction in NO_3^--N leaching by up to ~80% without a reduction in crop yield (Quemada et al. 2013). Overall, good management of irrigation reduces drainage, which in turn reduces NO_3^--N leaching. For example, the use of deficit irrigation [application of the amount of irrigation water less than the full crop evapotranspiration, with applications mainly limited to drought-sensitive growth stages (Geerts & Raes 2009)], leaves room in the soil profile for the rain that may fall. However, the decision on irrigation should be based on plant water requirements, soil water availability, system delivery, rainfall and predicted rainfall (Thomas et al. 2021). This technology is meant to reduce drainage, and therefore keep the nitrates within the crop root-zone. This is a low-cost technology, of moderate effectiveness.

3.2.2 Fertigation

Fertigation is directly linked to irrigation scheduling (Section 3.2.1) and is applicable across the three sectors. Fertigation is the agronomic operation in which fertiliser is dissolved in the irrigation water and delivered to the root zone by the irrigation system (Hagin & Lowengart 1995; Incrocci et al. 2017; Reddy et al. 2017). This combination provides the technical capacity for precise mineral nutrition, both spatially and temporally, thereby allowing high nutrient use efficiency (kg dry matter (DM)/kg nutrient supplied). The general idea is to apply fertilisers in little amounts but more often, which reduces the amount of residual soil N. Applications should be based on crop demand and soil supply. This is a low-cost technology (Table 4), once irrigation infrastructure has been set up, and is of moderate to high effectiveness. In New Zealand, centre pivot fertigation (Section 3.4.1) with controlled uniform or variable application to meet the site-specific needs of the crop, over a large area (50 ha or larger) is being adopted (Hedley 2015). Fertigation should be used in conjunction with soil/plant testing (Sections 3.2.3) or other DSS tools (Sections 3.4) so that estimates for the fertiliser demand by the crops are determined before application. There is a lack of information on fertigation in tree horticulture in New Zealand (Gentile et al. 2022); however, it has been used successfully in other countries (e.g. Incrocci et al. 2017; Reddy et al. 2017). Fertigation could be one of the most effective and low-cost technology in perennial fruits, in conjunction with drip irrigation (Section 3.4.1) which will have a one-off cost, with a low ongoing cost during the life of the perennial trees.

The other benefits derived from use of fertigation are reduced N_2O emissions and soil compaction, and indirectly reduced soil erosion and fuel CO_2 emissions from the fewer tractor passes required for fertiliser application.

There are some challenges with this technology (Thomas et al. 2021): (1) the fertilisers designed for fertigation are relatively more expensive, as they need to be sufficiently soluble to flow through the system, which also needs routine maintenance to clean pipes and emitters, and (2) it is not practical when soils are wet, to avoid drainage and NO_3^--N leaching. However, savings can be made where fertiliser use efficiency increases. Although available in New Zealand, the expertise is limited.

3.2.3 Soil testing and plant tissue testing

Both soil testing (Curtin et al. 2017) and plant tissue testing (Fageria 2003) or plant chlorophyll content (de Ruiter & Davis 1996; Chakwizira et al. 2020) can be used across the three sectors. They are used to inform soil and crop nutrient status, respectively, and therefore estimates of nutrient requirements. Soil tests are done at the start of the season to calculate the first N-application rate (Olfs et al. 2005), while plant tissue tests substantiate the decision of the grower on the timing and the application rate for a given field during the vegetative period. In-field methods like plant-sap/petiole nitrate test, chlorophyll-meter measurements, and optical sensors provide additional information at a very reasonable effort in terms of costs and time involved for a farmer. Both soil and plant tissue tests are usually accompanied by some calculations of N requirement, based on soil N availability or critical tissue contents. However, the increasing popularity of the chlorophyll measurements with hand-held devices, e.g., Yara N-tester, which gives corresponding N fertiliser rates (kg/ha) (Olfs et al. 2005; Chakwizira et al. 2020), could make this the technology of the future.

These technologies are ideally used as part of the nutrient planning systems and a DSS tool. Plant tests should be used in conjunction with soil tests. Chlorophyll and canopy reflectance sensors required specific methods to be developed (Olfs et al. 2005; Chakwizira et al. 2020). Most of these are relatively low cost to run, and highly effective. However, some, e.g., sensors have a one-off cost, with a low ongoing cost. It is unclear how widely the sensors/reflectance technology is being used in New Zealand, but the use of chlorophyll content tests (e.g. Yara N-Tester) is increasing (Chakwizira et al. 2020). The use of N sensors is currently being trialled in the arable sector in North Canterbury (https://www.nzherald.co.nz/the-country/news/cust-farmer-quantifying-the-benefits-of-sensor-based-nitrogen-application/C6ASAMWGN5DB7NJYKBJPGFI7BU/), a region that has similar weather conditions to Otago.

Soil testing for P typically requires less frequency, but it is important to apply P fertiliser needed by the crops, as excess P can easily be lost into surface water through run-off.

3.2.4 Fertiliser management

The key elements for good fertiliser management are based on the 4R Nutrient Stewardship guidelines (Johnston & Bruulsema 2014) of applying the right rate (kg/unit area), right timing, right placement and right fertiliser source. Fertiliser management is a widely proposed global technology to mitigate NO_3^--N leaching (Shrestha et al. 2010), and has been reported widely, including in New Zealand (Williams et al. 2003; Reid & Morton 2019). This technology can be used across the sectors.

This is a low-cost technique, but its effectiveness is compromised by the fact that it does not affect the leachable NO_3^--N that is released from the crop residues, and mineralised SOM (Section 1.3), which is the main source of leached NO_3^--N over winter from arable and vegetable crops. Fertiliser management should be applied as part of GMP, alongside soil/plant testing and use of sensors (see Section 3.2.3). It is commonly used in the New Zealand arable sector.

There are no available data on losses of P in runoff from arable cropping systems in New Zealand (Payn et al. 2013). Presumably losses are low because most arable crops are grown on flat land and fertiliser P is mostly soil incorporated, thus with negligible P or sediment run-off.

Phosphorus demand in many vegetable crops is minor (20–50 kg/ha) compared with those of other macro-nutrients like N and K (commonly 200–400 kg/ha). However, the agronomic P thresholds for vegetable crops are much higher than those for arable and forage crops despite similar P uptake values (Payn et al. 2013), e.g. Olsen P values of ≥35 (Reid & Morton 2019) for vegetable crops compared with 20–25 for the arable crops. The scientific basis for these higher threshold values needs to be clarified.

The nutrient requirements of different perennial tree and vine fruit crops are at best complex and relatively specific to individual crops, and at worst, very poorly known for many of these crops (Payn et al. 2013). There is need for more work to be done in this space (Gentile et al. 2022).

3.3 Remedial technologies

These are technologies used to minimise the ‘spread’ of NO_3^--N leachates and are designed to reduce the concentration of NO_3^--N in drainage water before it is discharged into waterways (Balcerzak et al. 2022). These could be in the form of grass filter strips [a band of managed grass which acts as a buffer between a water body, and potential contaminant loading source] or riparian buffers [a band of managed vegetation between agricultural land, and waterways, low costs: $100 to $250/ha across the sectors] or controlled drainage [preventing NO_3^--N from leaving the system using a weir or water flow control to raise the water level in the drainage outlet and hold water in the drain]. For P loss control, sediment traps, excavations in the bed of a watercourse to slow water flow, encourage sediment filtering. These are tertiary methods. Establishment ranges between $750 and $1,300 ha/year. These apply mostly to the cropping/vegetable sectors.

3.4 System optimisation

System changes and optimisation need a high degree of knowledge and understanding of the crop-soil system (Thomas et al. 2021). While researchers and growers may be able to understand this, the relationship is not straightforward, as the interactions between the different crops and different soils, and weather conditions makes interpretation of nutrient outcomes difficult. Decision support systems (DSS) have now been developed for cereals (Jamieson et al. 1998; Armour et al. 2002), maize (Reid et al. 1999; Li et al. 2009), potatoes (Jamieson et al. 2006), sweet corn, tomatoes (Reid et al. 2005), carrots (Reid 2005), and numerous forage brassica species (Wilson et al. 2006; Chakwizira et al. 2011, 2012). Recently, the Nitrate Quick Test Mass Balance Tool for arable and vegetable crops was released (FAR 2020), while the Sustainable Vegetable Systems (SVS) tool is being developed for vegetable crops (Michel et al. 2021), which will cover nitrate leaching under vegetable rotation systems (https://potatoesnz.co.nz/rd-project/svs-programme/).

Some of the DSS tools are publicly available through the FAR website, e.g. the Wheat Calculator (Armour et al. 2002), AmazeN (Li et al. 2006; Li et al. 2009), and the Nitrate Quick Test. The OVERSEER® Nutrient Budgets model is available (https://www.overseer.org.nz/) but there is a cost associated with signing up. However, some of the DSS tools are proprietary (e.g. the forage brassica calculators) and therefore are available only to farmers/landowners through rural professionals from the relevant owners/companies. The DSS tools have a wide functionality range, with some providing fertiliser recommendations (rate x timing) for nitrogen only or for multiple nutrients simultaneously. Some DSS tools also estimate NO3- -N leaching losses (e.g. Jamieson et al. 2006), although the accuracy of these estimates is contentious. A cropping systems (OVCrop) N balance module was incorporated into the OVERSEER® Nutrient Budgets model (Cichota et al. 2010), but these [horticultural and cropping modules], have not been as widely tested or updated as frequently as the pastoral module.

3.4.1 Irrigation design (GMP+)

This is relevant only to irrigated crops. Irrigation design has been widely researched and used globally (Evans et al. 2013; Hedley 2015). The key principle is to apply the right amount of water, at the right place, at the right time. Furthermore, application rates should not exceed the soil infiltration rates (Thomas et al. 2021), as poor irrigation can result in greater NO_3^- -N leaching losses than poor fertiliser management.

Irrigation design technologies include variable rate irrigation, drip or micro-irrigation, centre pivot and fixed grids. Different technologies have different applicability, and therefore are suited to different farming sectors, e.g. drip or micro-irrigation is more suited to perennial (tree) horticulture (Reddy et al. 2017), while centre pivots are suited to arable crops (Hedley 2015). In fruit and vegetable production, drip irrigation is the most common system used for fertigation (Section 3.2.2) and requires the most knowledge for effective use (Reddy et al. 2017).

Drip irrigation is the most efficient method to deliver water and nutrients to a plant, but is not always practicable (e.g. in cultivated soils) (Payn et al. 2013; Reddy et al. 2017). It is expensive to install and requires regular maintenance and therefore, only high-value crops are considered. Drip irrigation is suitable for all soils, and for perennial tree crop, as it has a one-off installation cost, with a low ongoing cost. There is also a variant of this technology, subsurface drip irrigation, being trialled in Maniototo, Central Otago (https://www.nzherald.co.nz/the-country/news/cust-farmers-ready-for-data-gathering-from-subsurface-irrigation-trial/G3MK7W7RVVH2NFA3PTN7XNOT5A/). Although this is being trialled on permanent pasture, the principles can be applied to the arable and horticulture sectors described in this report.

Other benefits of properly implemented irrigations designs include reductions in N_2O emissions, improved water, and nutrient use efficiency, reducing the risk of P and sediment run-off losses.

3.4.2 Precision agriculture (input management)

Precision agriculture uses proximal and remote sensor surveys to delineate and monitor within-field variations in soil and crop attributes, guiding variable rate control of inputs (Hedley 2015), so that in-season management can be responsive, for example, matching strategic N fertiliser application to site-specific field conditions. It uses technologies like maps/sensors followed by variable rates of applications for fertilisers or irrigation. It is widely used globally and can be used across the sectors. The technology applies directly to fertiliser and irrigation application, and has the indirect benefit that fertilisers are not applied when soil supply are adequate. This has been widely used in broadacre arable crops (Robertson et al. 2012). However, there is lack of information on its use in vegetable crops. Its principles encompass both irrigation scheduling (Section 3.2.1) and fertiliser management (Section 3.2.4).

3.4.3 Precision fertiliser management (fertiliser type)

Precision fertiliser management covers the use of slow-release N fertilisers (Table 4), envisioned to release N slowly so that there are always small but uniform amounts within the root zone. However, the challenge is to match the rate of release with plant requirements [which vary during the growing season]. Precision fertiliser management is used and available in New Zealand (Edmeades 2015) but is more challenging with short-rotation vegetable crops (Thomas et al. 2021). It is comparatively of moderate cost, but less effective (Table 4).

3.5 Integrated crop management systems (ICM)

This is a whole-system approach that integrates optimised management practices/technologies suited to the grower’s rotations, to produce a greater NO_3^--N leaching reduction than any one individual technology (Zhang et al. 2018). The focus of the whole system is to minimise excess N, run-off, and drainage in the crop rotation. Examples of ICMs include reducing fertiliser application (Section 3.2.4), cover cropping (Section 3.1.1), use of soil and/or plant testing to guide decisions (Section 3.2.3), and precision N and water management (Section 3.4). The expectation is the incorporation of several technologies discussed here (Table 4) and these may be delivered through a DSS (Section 3.4).

The costs for ICM may vary from low to moderate depending on the range of interventions but can be highly effective if properly implemented. In New Zealand, ICMs could be part of the Farm Environment Plans (https://planning.org.nz/Attachment?Action=Download&Attachment_id=4134). There are few sources of information for the whole-system approaches, compared with individual management components (Thomas et al. 2021), which is a reflection of the challenges of setting up the more complex experiments required for systems analysis. Therefore, it is unclear how widely this is being used in New Zealand.

4 Other technologies (GMP+)

The GMP+ technologies are more suited to high-value crops (vegetables), as the costs of establishment and maintenance of infrastructure are very high (>NZ$500,000).

4.1 Soilless growing in greenhouses (hydroponics)

Soilless plant cultivation in an almost completely controlled environment is a relatively modern cultivation technology and is used almost exclusively in greenhouses (Fussy & Papenbrock 2022). This is used for a range of high-value crops, and more suitable for high-value vegetable crops. The technology uses a range of inert growing media [inorganic, organic, or synthetic]. The advantage of soilless growing is the ability for full control over nutrient inputs and environmental conditions.

This technology is already used in New Zealand (Payn et al. 2013; Thomas et al. 2021) for high-value vegetable/fruits, e.g. capsicums. Challenges include waste materials with high N content, and hence the need for treatments, which can be costly. The cost of greenhouses is also very high, ranging from NZ$800,000 to $3,000,000,000 per ha. Further costs will be incurred in setting up more advanced nutrient capture systems.

4.2 Vertical farming (Growing indoors)

Vertical farming systems are much more intensive systems than greenhouses. They can be broadly divided into two categories (Beacham et al. 2019; Petrovics & Giezen 2022): those comprising multiple levels of traditional horizontal growing platforms, and those where the crop is grown on a vertical surface. Vertical farming uses a great deal of artificial light, high technological control, sensing and operating systems. They have more control over nutrient inputs, temperature, and moisture than there is in greenhouses.

The system captures all nutrients, but still requires the removal of N and P before the waste nutrient solution is discharged. Not all crops are suited to growing in this manner, but those of high value with short storage lives are, e.g. salad leaf vegetables. The key challenge is the prohibitive costs of establishment, as they are an expensive option. They have high energy costs, but could result in reduced chemical [e.g. pesticide] use.

5 Summary

The main points from the review, split into either land or plant based GMPs and GMP+ are listed below.

5.1 Land-based GMPs

- Manage period of exposed soil between crops to reduce risk of erosion, overland flow, and leaching.
    - Harvested areas are re-sown as soon as practical.
    - Use cover crops to reduce nutrient losses, and improve nutrient use and SOM.
    - Retain native vegetation in gullies, steep slopes to regulate run-off/reduce soil movement and provide filter area prior to water entering streams.
- Monitor soil P contents and maintain them at or below the agronomic optimum for the farm.
    - Regular, ongoing soil testing. Different crops have different agronomic P thresholds.
    - Leave unfertilized zones/strips besides creeks/drains/stormwater flood zones.

5.2 Plant-based GMPs

- Manage the amount and timing of fertiliser inputs, considering all sources of nutrients, and match the plant requirements and minimise risk of losses.
    - Manage nutrient supply from ALL sources: soil, crop residues and SOM.
    - Regular soil testing to identify nutrient (N and P) needs.
    - Use expert guidelines: crop calculators, codes of practices and expert opinions.
    - Apply fertiliser strategically, to meet agronomic requirements.
    - Use nutrient budgets.
    - Side dressing/split application of fertilisers.
- Manage the amount and timing of irrigation inputs to meet plant demands and minimise risk of leaching and run-off.
    - Irrigate only to replace soil moisture deficit, for fertigation, prepare soil for cultivation, and for frost protection.
    - Maintain soil moisture between stress point and field capacity: need knowledge on evapotranspiration, field capacity, and use of probes to achieve this.
    - Volume applied should be informed by crop type, growth stage, soil type and field capacity.

5.3 GMP+ Options

- Design, calibrate and operate irrigation systems to minimise the amount of water needed to meet production objectives.
    - Follow industry codes of practice for any new development/upgrade or redevelopment.
    - Irrigation systems should be evaluated annually to achieve optimal performance.

- Soilless growing in greenhouses.
  - Suitable for high-value crops.
  - Full control over nutrients and environmental conditions.
  - Very expensive; and effective.
- Vertical farming.
  - Grown on multiple levels of traditional horizontal platforms or on vertical surfaces
  - High-value crop with short storage lives.
  - Full control over nutrients and environmental conditions.
  - The most expensive and effective technology.

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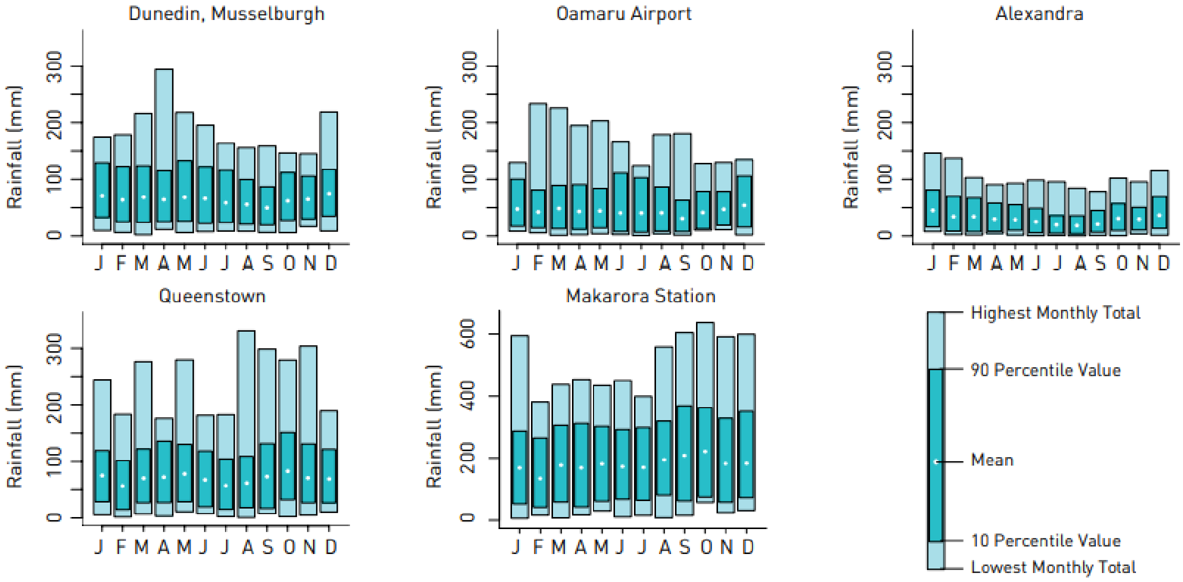
Appendix 1. Land use in the Otago region, New Zealand

Crop[1]	Hectare	Comments
Cereals	**7510**	Nothing or little grown in Dunedin
Wheat	1862	96% other uses, 4% milling. 95% in Waitaki/ Clutha regions. Not grown in QT-Lakes or Dunedin
Barley	4017	80% in Waitaki/Clutha regions. Grown in ALL 5 Districts
Oats	705	69% in Clutha, 27% in Waitaki, not grown in QT-Lakes or Dunedin
Other cereal grains	465	Throughout the region, but 75% in Waitaki/Clutha regions
All other grain and seed crops	462	Grown in ALL areas
Total cereals	**7511**	Nothing or little grown in Dunedin
Tree horticulture		
Berryfruit	36	52% in Dunedin (19 ha). Not grown in Clutha
Grapes	1205	77% in Central Otago, 21% in QT-Lakes. Not grown in Dunedin or Clutha
Nuts [chestnut, hazel, walnut, macadamia]	150	57% hazelnuts, 43% walnuts. Not grown in Clutha
Olives	19	79% in Central Otago. Not grown in Dunedin or Clutha
Pipfruit [apples: 426.8 ha; pears: 9.0 ha]	436	Central Otago (99%)
Subtropical	1	Not grown in Clutha or QT-Lakes
Summerfruit		
Peaches	94	97% in Central Otago, 3% Waitaki
Apricots	306	96% in Central Otago, 4% Waitaki
Cherries	578	99% in Central Otago, 1% Waitaki
Nectarines	129	98% in Central Otago, 2% Waitaki
Plums	56	91% in Central Otago, 9% Waitaki
Total Fruits	**3010**	Majority of the crops are grown in Central Otago
Vegetable horticulture		
Potato	195.6	56% in Clutha, 42% Waitaki. Not grown in Dunedin
Broccoli	104	92% in Waitaki, 8% in Dunedin
Cabbage	23.7	45% in Dunedin, 55% in Waitaki
Carrots	2.6	96% in Clutha, 4% Waitaki
Cauliflower	27.5	67% in Waitaki, 33% in Dunedin
Lettuce	14.4	69% in Waitaki, 31% in Dunedin
Leaf vegetables	5.4	50% in Waitaki, 50% in Dunedin
Asparagus	7.2	All in Waitaki
Cooking herbs	1.1	82% QT+Lakes, 19% Central Otago
Other vegetables	43	
Outdoor Vegetable	**425**	62% in Waitaki, 27% in Clutha. Lowest (2.3%) in Central Otago & QT+Lakes

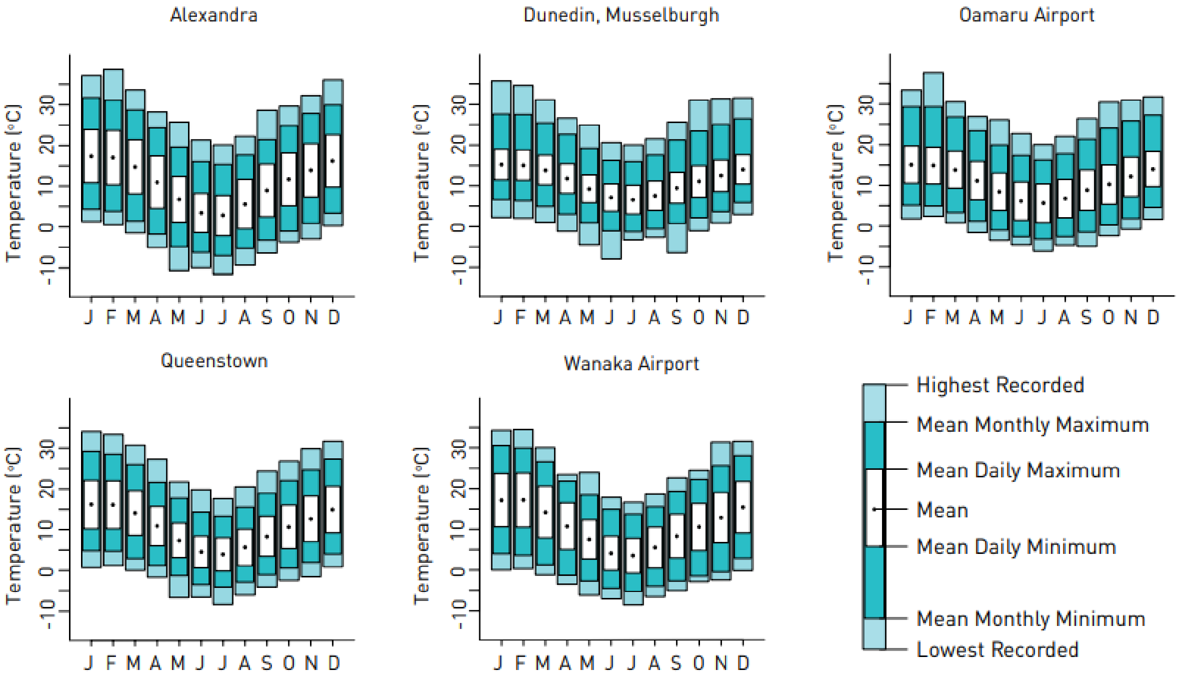
[1] We have excluded field & seed peas (349 ha), other pulses (135 ha) and vegetable seeds (330 ha)

Appendix 2. Weather [rainfall & temperature] data for the key districts in the Otago region (https://docs.niwa.co.nz/library/public/NIWAsts67.pdf)

Rainfall: Monthly variation of rainfall for selected Otago locations from all available data



Temperature: Monthly variation in air temperature for selected Otago locations



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