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Options to mitigate nutrient leaching from commercial vegetable production

Thomas S, Trolove S, Fraser P, Langer S, van der Klei G, Michel A, Greer G, Gee M, Searle B, Hall M

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Report prepared by:

Steve Thomas
Scientist, Climate Smart Systems
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Report approved by:

Paul Johnstone
Science Group Leader, Cropping Systems & Environment
June 2021

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Executive summary

Options to mitigate nutrient leaching from commercial vegetable production

Thomas S[1], Trolove S[2], Fraser P[1], Langer S[1], van der Klei G[1], Michel A[1], Greer G[1], Gee M[1], Searle B[2], Hall M[3]
Plant & Food Research: [1]Lincoln, [2]Hawke's Bay, [3]Auckland

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There is a significant lack of information about available mitigation strategies that may reduce nutrient leaching in vegetable production systems. Commercial vegetable production in New Zealand is relatively intensive, relying on high nutrient inputs, resulting in risks to water quality. The Essential Freshwater (EF) Package raised questions about current vegetable production practices and nutrient management. In order to maintain or improve water quality, current practices will need to be adjusted to reduce nutrient leaching, to meet limits set by local governments and thus maintain the ability of the industry to produce vegetables sustainably.

The Ministry for Primary Industries (MPI) engaged The New Zealand Institute for Plant and Food Research Limited (PFR) to:

- Conduct a worldwide literature review to assess and analyse mitigation methods and technologies used to achieve significant reductions in nutrient leaching in vegetable production systems
- Provide expert opinion regarding the current status of the use of the identified technologies and their potential suitability for adoption in New Zealand
- Provide an indication of the cost of implementation for each of the technologies.

A long list of 28 technologies that can have impacts on reducing nitrate leaching was identified from a global scan of the literature. Information on costs of implementation of these technologies was challenging to find and the results are indicative only and as such, need to be treated with caution.

We assessed each of the identified technologies for both their mitigation potential and their estimated cost of implementation, and subsequently ranked them on a matrix graph (Figure ES1).

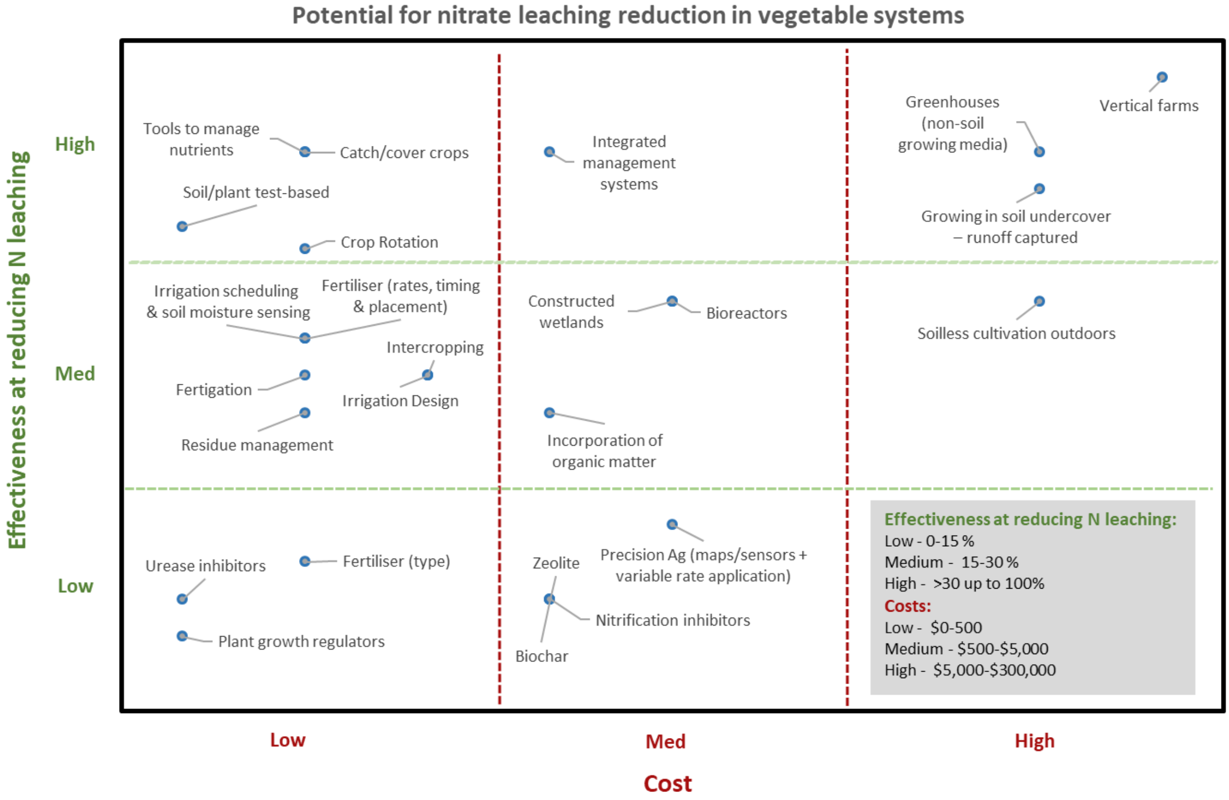

Figure ES1. Summary matrix of the effectiveness of potential leaching mitigation technologies and their implementation costs for use in vegetable production (indicative costs are in NZD). Where mitigations overlap, they have similar costs and effectiveness.

Our review of options highlighted that:

- There were no “silver bullet” technologies
- Most of the technologies are already available in New Zealand in some form
- High-cost technologies tend to have high potential for mitigation of nutrient losses, but their high costs mean that they are unsuited for large-scale, lower-value vegetable cropping
- There are a number of low-medium cost approaches and technologies that will minimise nutrient losses if applied well
- More integrated approaches have the greatest impact on reducing leaching
- The effectiveness of a number of the technologies will depend on specific environmental conditions (soil, climate) as well as crop and crop-rotation factors
- Combining some or all of these technologies will achieve best practice for minimising N leaching in vegetable cropping systems
- There are a number of approaches and technologies for which there is little information on their effectiveness, and we have not scored these as highly.
    - In particular, some of the precision farming techniques have been slow in uptake, but given improvements in sensing and computing capability we expect they will become more important in the future

    - Similarly, there is a large range of decision-support tools to manage nutrients and water that are available globally and some of these are available in New Zealand; however, their uptake is also understood to be limited
- There are some low-cost options that may have lower mitigation potential but are easily implemented, such as applying urea-based fertiliser with a urease-inhibitor
- In many of the studies we reviewed in our global scan, the comparison of the technology was often related to practices that we would not consider 'good practice' in New Zealand, making it difficult to compare and therefore assess how well a technology will perform in New Zealand.

Our recommendations for future investigation are to:

- Understand the range of technologies and approaches currently being used, and how they are being used
- Address the large gap in our understanding of the barriers to adoption of mitigation approaches
- Using process-based system models, undertake whole-system modelling approaches to understand the opportunities for technologies to mitigate leaching
- Investigate the growers' need for 'grower-friendly tool(s)' that would help to manage their complex nutrient, water and crop requirements.

For further information please contact:

Steve Thomas
Plant & Food Research Lincoln
Private Bag 4704
Christchurch Mail Centre
Christchurch 8140
NEW ZEALAND

Tel: +64 3 977 7340
DDI: +64 3 325 9635
Email: Steve.Thomas@plantandfood.co.nz

1 Introduction and background

Commercial vegetable production in New Zealand often occurs on deep mineral soils, which are commonly subjected to frequent, often intensive, cultivation. Growing periods can be quite short depending upon the crop, and fertiliser practices vary widely depending on the crops grown, the environment in which they are grown, and grower preferences.

To meet new national objectives outlined in the Essential Freshwater (EF) Package, vegetable production practices and nutrient management will need to be adjusted to reduce nutrient leaching and meet the limits set by local governments, and maintain the growers' ability to produce vegetables sustainably. The Ministry for Primary Industries (MPI) and other stakeholders are interested in reviewing and analysing mitigation methods and technologies that have been used to achieve significant reductions in nutrient leaching in vegetable production systems worldwide, and in an indication of their suitability for adoption in New Zealand.

1.1 The project

1.1.1 Deliverables

Long-list summary:

- A long list of technologies and growing methods that significantly (over 30%) reduce nutrient leaching from vegetable growing, based on a scan of the global scientific literature
- The long list should include 10–20 (or more) mitigations used by growers outside New Zealand and provide a high-level description of each.

Microsoft® Excel® spreadsheet:

- A searchable spreadsheet that summarises, for each technology or method: nutrient leaching reduction, cost, and environments in which the technology has been applied, with supporting reference(s) and an indication of whether they are suitable to New Zealand growing conditions. This should also note if any options have not been peer-reviewed, or look promising but have insufficient data.

Final report:

- Context of work
- Long-list summary
- A graph/matrix that plots each technology/method according to the potential effectiveness of nutrient leaching mitigation versus estimated or indicative cost
- Ranking of a long list to recommend the most promising options for New Zealand vegetable growers and discussion about additional benefits and trade-offs. These should include any risks for achieving other sustainability goals, such as increasing carbon footprint, or reducing biodiversity
- Recommended next steps.

2 Methodology

2.1 Aims

- Conduct a worldwide literature review to assess and analyse mitigation methods and technologies used to achieve significant reductions in nutrient leaching in vegetable production systems
- Provide expert opinion regarding the current status of the use of the identified technologies and their potential suitability for adoption in New Zealand
- Provide an indication of the cost of implementation for each of the technologies.

2.2 Scope

Particular emphasis was placed on nitrogen (N), but phosphorus (P) and sediment were also of interest. Nitrogen in the form of nitrate is much more readily leached than P. Nitrate is poorly held by the soil, whereas P is strongly bound to aluminium and iron oxides and to clay, so leaching rates are low from horticultural soils.

Leaching losses measured in a six-year study on growers' properties [1] ranged from 13 to 193 kg/ha/y for N and were 0.05–0.33 kg/ha/y for P over the eleven vegetable and arable properties, with higher losses on the vegetable properties. Therefore, the nutrient we have focused on in this global review of nutrient leaching losses has been N. Phosphorus and sediment losses are also important for water quality. These are largely lost by overland flow. Large losses of P (>140 kg P/ha) and sediment (>37 t/ha) from overland flow have been reported under vegetable production over a 9-month period in Pukekohe on sloping land where soil P contents are high [2]. Much smaller losses would be expected on flat land [3]. Some of the technologies identified to mitigate N leaching losses may reduce or increase losses of P and sediment, and this additional benefit or drawback has been noted in this report.

2.3 Developing the long list

We developed a list of appropriate keywords and supplied them to a Knowledge Navigator from The New Zealand Institute for Plant and Food Research Limited (PFR), who conducted an initial literature search as follows:

Topic: (leach* or runoff or excess* or surplus or loss*) near/10 (nitrogen or nitrat*) and vegetable* and (reduc* or mitigat* or control* or manag* or alleviat*) 1128 results, 114 selected.

Proquest noft((leach* or runoff or excess* or surplus or loss*) near/10 (nitrogen or nitrat*) and vegetable* and (reduc* or mitigat* or control* or manag* or alleviat*)) 802 results, 111 selected, 69 after duplicates removed.

Over 500 references were found via the initial search. After identifying several key papers of interest, about 200 additional references were located. Over 700 references were assessed and a "long" list of the most appropriate ones selected for further investigation. Sources included journal papers, reports, book sections, conference papers and web pages. Furthermore, the team approached other experts to check the completeness of the list and efficacy of the mitigations.

2.4 The MS Excel spreadsheet

Initially the references were imported into an Excel spreadsheet. As the information was assessed, the review team used the spreadsheet to record relevant information. A robust process was followed to assess the mitigation technologies or method reported in each report, paper or web page using a range of key criteria:

- Identifying the primary or secondary technology
- Nitrate leaching reduction – absolute/relative values, central tendency/range reported
- Experiment type(s)
- Amount of N applied
- Crop type(s)
- Soil type(s)
- Where the technology was tested
- Estimates of cost(s)
- Trade-offs (e.g. other water contaminants, greenhouse gases).

Using these criteria, a method or technology was assessed to determine whether it was relevant as a promising technology that required further investigation. The design of the spreadsheet enables filtering of the technology and criteria to help summarise the merits of each technology across the range of conditions reported.

The promising long list was peer-reviewed to check the validity of assessments. This was to ensure no promising technologies were omitted, and key information was captured, to ensure an overall consistency in approach had been followed.

Initially the technologies were grouped based on the keywords used in the searches. This grouping was refined as different technologies emerged and was further aggregated at a higher level as common approaches emerged. Using these groupings, a summary spreadsheet was created that could be filtered and searched.

2.5 Ranking the promising options

Ranking for each technology was agreed in a workshop-process with the research team, which included experts in crop agronomy, soil science, crop physiology and nutrient leaching. Each technology was discussed by the group and assessed for both its mitigation potential and the estimated cost of implementation. This process allowed the team to compare the merits of the different technologies for their mitigation potential versus the estimated capital and operational costs that would be incurred. The technologies were then ranked relative to each other.

It was agreed to use a semi-quantitative approach to rank the technologies (Table 1). This approach was necessary as the effectiveness of each mitigation depended greatly on (i) the conditions in which they were tested, and (ii) the controls that were used to contrast with the reduction; i.e. when compared with a poorly managed system, the mitigation will appear much more effective than against a well-managed system. Necessarily, the ranking was strongly based on expert assessment. The team, with considerable experience in quantifying leaching in cropping systems, were careful to do their best to assess the reported leaching reductions in relation to environments and management systems that are appropriate for New Zealand vegetable systems.

Information on costs of technologies was challenging to find and the results need to be treated cautiously. Cost information was primarily based on what is reported in the overseas literature and/or was readily accessible from New Zealand sources. In most cases, the costs cover a large range depending on the environment and complexity of the system. For example, there are many options for irrigation or fertiliser application, selection of which depends on a range of environmental and agronomic management factors (e.g. crop type, crop area, cultivation and seed bed preparation methods, soil, climate). This was further complicated because we needed to attempt to account for the capital, operating and maintenance costs in the assessment, requiring a number of assumptions on the technology or methodology. More detailed research is required to better define these values.

Table 1. Ranking criteria for evaluating nutrient leaching mitigation technologies for vegetable crops.

Ranking	Mitigation effectiveness %	Estimated cost of implementation $NZ/ha
Low	0–15	0–500
Medium	15–30	500–5000
High	30–100	5000–3,000,000

Rankings were entered into the summary spreadsheet and the results of the ranking plotted to visually explore the effectiveness of the mitigation technology against the cost of implementing the technology.

3 Results and discussion

Nitrate leaching mitigation technologies can be categorised as either preventative or remedial. Preventative in-field mitigation technologies are based on minimising the amount of residual or excess N that is available to be leached and the risk of drainage. In contrast, remedial technologies are those where the leachate or runoff is captured and the nitrate and other contaminants are removed off-site or attenuated. The amount of residual N in the soil is a function of the N inputs from fertiliser, soil organic matter, legumes and crop residues, N uptake by the plant and N losses to air and water. Drainage is largely a function of soil water status, soil type and depth, plant water-use and rooting depth, and climate. Hence, there are large regional differences in leaching and effectiveness of mitigation due to differences in climate and soil. Suitability and effectiveness of N leaching mitigation strategies will also depend on slope and topography. Hence, it is important to consider the technology within the context for which it is designed.

While there are a large number of papers and reports that have reported reduction in nutrient leaching values due to a variety of mitigation practices, it was often challenging to quantify actually how effective the mitigations were. This was particularly the case when the controls against which the nutrient leaching reductions were compared were not good practices to start with. Given many scientific experiments are designed to test for the effects of different treatments, this might mean some treatments are exaggerated (e.g. a worst-case scenario). Conversely, if compared with an existing good practice, the effectiveness of the mitigation is going to appear to be less. For example, there are several studies demonstrating large reductions in nitrate leaching when irrigation scheduling was improved based on soil water conditions and crop requirements, compared with inefficient, fixed watering schedules. This is not a fair comparison against what good or expected practice would be; i.e. we have an expectation that New Zealand growers are already using some form of irrigation scheduling. Similarly, there are overseas examples where the comparison of fertiliser applications is made with poorly managed applications.

As described above, not only is the reported effectiveness of mitigation technologies and approaches affected by the management conditions, i.e. nutrient management and irrigation, it is also affected by soil, slope and climate, amongst other factors, which have a large influence on nutrient leaching responses. Consequently, our filtering of reported mitigation reductions in nutrient leaching was strongly influenced by both expert opinion and the evidence available.

Good management practices are already expected of New Zealand growers and are part of New Zealand Good Agricultural Practice (NZGAP). For example, there is a Code of Practice for Nutrient Management [4] in NZGAP to implement good and best management practices. Good management practices (GMP) are entry-level practices that all growers could expect to undertake to manage nutrients. Best management practices (BMP) are advanced mitigation options that often require significant investment which may present a barrier for uptake, especially for smaller growers. Also, growers are expected to follow good practice for reducing run-off and sediment, following the Guidelines for Erosion & Sediment Control Guidelines for Vegetable Production [5].

3.1 Mitigation technologies – nitrate leaching reduction vs cost

3.1.1 Long list

The long list of mitigation options is summarised in Table 2, with mitigations categorised into groups of high, medium and low potential for minimising the loss of N via leaching in vegetable cropping systems. Within each mitigation effectiveness category, the technologies are also ranked based on the cost of their implementation, on the basis that low cost is preferable to high cost, i.e. a highly effective mitigation technology that has a low implementation cost is ranked above a highly effective mitigation technology that is much more costly to implement. Figure 1 and Table 2 summarise the data from the long list.

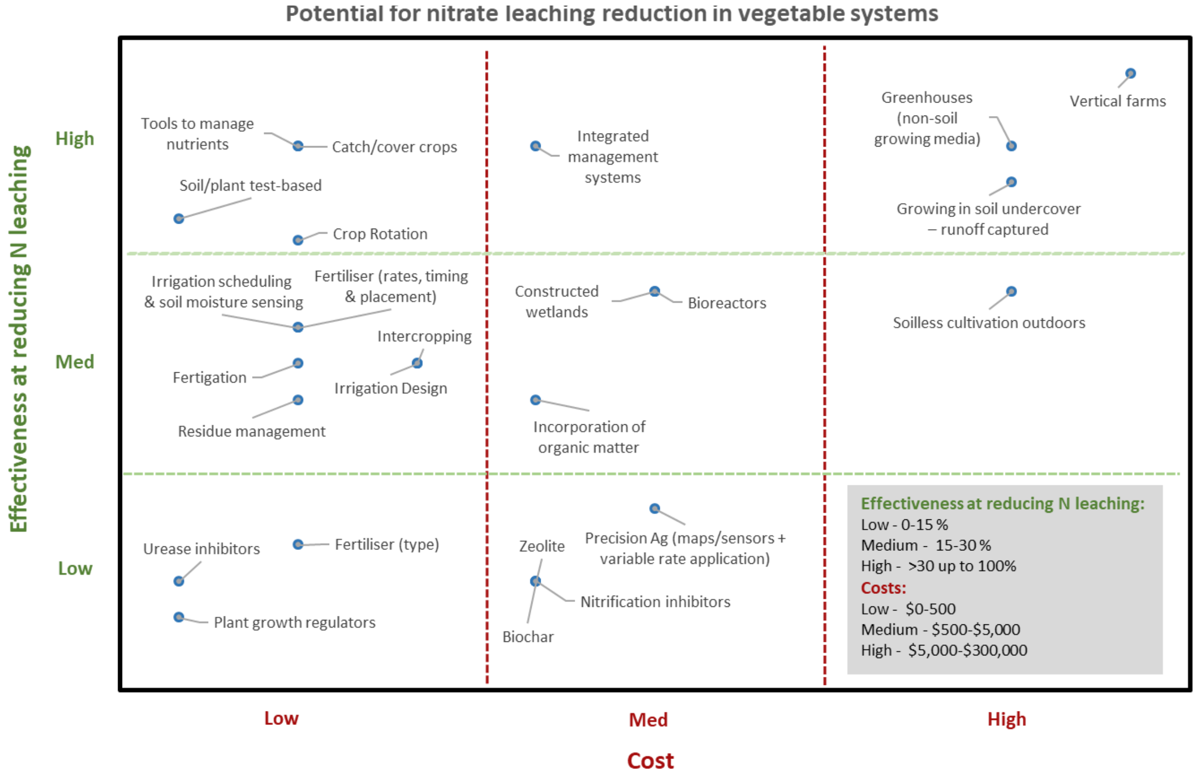

Figure 1. Summary matrix of the effectiveness of potential leaching mitigation technologies and their implementation costs for use in vegetable production (indicative costs are in NZD). Where mitigations overlap, they have similar costs and effectiveness.

Table 2. The long list of potential mitigation technologies for nutrient leaching in New Zealand.

Technology Group – and subgroup	Description	Mitigation narrative
Mitigation effectiveness – High		
Catch crops or cover crops (Improved management)	Catch crops are sown to take up nitrate to prevent leaching. They are generally grown over winter when the leaching risk is greatest, but should be considered for any periods of fallow. They are typically incorporated into the soil or removed prior to the establishment of the next crop. Catch crops are generally species that grow well over winter and are easy to establish, such as cereals or ryegrass.	Probably the most widely recommended mitigation for field-grown vegetable crops, and used worldwide. Global meta-analysis found a 56% reduction in leaching attributed to the use of catch crops. Greatest mitigation benefits occur when planted early. The benefit reduces when sowing occurs closer to winter when crop growth slows and drainage tends to increase. Hardest to employ in wetter years when unable to use equipment to establish crops [6,7]. Cost: one of the lowest of any of the technologies. Normally there are no special machinery requirements. They are relatively low cost to establish, grow and harvest. There may be a negative impact on profits if the catch crop (i) replaces a higher value crop or (ii) has no marketable value. If the crop is not sold, the capture of nitrogen (N) should be regarded as a source of N for the following crop if it is incorporated into the soil, which reduces fertiliser costs. May provide additional benefits e.g., addition of organic matter or fixation of N depending upon the cover crop grown. Also reduces phosphorus (P) and sediment runoff losses, compared with fallow. Already widely used by farmers and growers in New Zealand.
Tools to manage nutrients (Precision fertiliser management)	Plans are designed to minimise N surpluses and supply N based on crop requirements. Central is a N budget that accounts for all sources and losses of N. An example of a decision support tool is a computer model that helps to account for the complex soil, plant and climate processes. Ideally linked to soil and plant testing.	Following a nutrient management plan is internationally accepted as good practice. Decision support tools provide growers with estimates of the crop N requirements and soil N supply to avoid adding excess N [8]. Global meta-analyses found leaching was reduced by about 60% when using decision support tools were compared with grower management. Note that grower management was experience-based, not based on scientific principles [9-13]. Main effects on leaching are reductions in N fertiliser application, but also accounting for surpluses of N from residues and soil organic matter. Cost: one of the lowest costs and highest benefits gained. Some tool development is supported by government funding designed to be standalone or incorporated into other software (e.g. PLANET, funded by Defra, UK). A number of western European countries, such as Denmark, require use and demonstration of fertiliser planning. In New Zealand, this could form part of a Farm Environment Plan.
Integrated crop management systems (Improved management)	A whole growing system approach that combines a number of technologies suited to the grower's rotation, to produce a greater N leaching reduction than one individual technology. This focus on the whole system is designed to minimise excess N, run-off and drainage in the crop rotation. The expectation is that this would incorporate a number of technologies listed above and below. May be delivered through a decision support system (DSS) tool.	There are few studies where an improved whole systems approach is compared with a standard or current system. This largely reflects the challenges of setting up more complex experiments required for system analysis. A UK study identified system changes that could reduce leaching by 30% [14,15]. The mitigation percentage will depend on the degree to which best management practices were being followed in the original system. If integrated crop management is included in nutrient management plans, then it would be expected that whole system management would reduce leaching even more than the values reported above. Examples of the integration of technologies include reducing fertiliser applications, cover cropping, and substitution of crops for lower leaching crops, use of soil and plant tests to guide decisions, precision N and water management, using DSS tools and sensors (see above). Costs: relatively low, depending on the range of interventions. May also result in decreased need for chemicals to control pests and diseases. There may also be some advisory costs. In New Zealand this could form part of a Farm Environment Plan. We are unsure how widely this is used in vegetable production in New Zealand.

Technology Group – and subgroup	Description	Mitigation narrative
Soil-less growing in greenhouses (New Technology)	Soil-less growing in greenhouses is used widely for a range of high value crops. It uses a range of growing media (inorganic, organic and synthetic). Advantages are that there is more complete control over nutrient inputs and environmental conditions, and all wastes can be captured and treated.	This system will also mitigate losses of other nutrients and sediment. The key factor to the mitigation effectiveness is the ability to contain the nutrients within the system or to limit their discharge. Poorer containment systems will allow nutrients to leach into the soil from the soil-less medium, whereas closed systems including nutrient purification result in little or no loss. Western Europe is imposing stringent regulations to avoid leaching, with zero emission of nutrients from soil-less cultivation in greenhouses by 2027 and reduced emissions from soil cultivation in greenhouses [16]. Costs for greenhouses are very high and range from $NZ800,000 to $NZ3,000,000 per ha. More advanced nutrient capture systems will increase these costs. Not all vegetables are suited to growing in this manner. Best suited to high value crops. May result in reduction of chemicals applied to control pests and diseases. Waste material can be high in N, so needs treating, which is costly. End-of-life disposal of greenhouses is also a consideration. Soil-less greenhouse systems are already used in New Zealand for high value vegetables/fruits – e.g. capsicums.
Growing indoors – Vertical farms (New Technology)	Much more intensive growing systems than greenhouses. Use of artificial light. High technology control, sensing and operating. There are many different forms and scales emerging [17]. Even more control over nutrient inputs, temperature and moisture control than greenhouse systems.	Applications in many forms worldwide e.g. Integrated green-walls (naturally-lit, enclosed within building envelopes); Appliance-scale self-contained plant production units (Flex Farm 288); Micro-scale automated personal plant incubators (MIT Food Computer); Shipping-container growing systems (LocalRoots Terrafarm, FreightFarms Greenery™, Greentech Growtainer™); Warehouse-scale controlled environment plant factories (Aerofarms) [17,18]. Few report the effectiveness of effluent disposal. These systems have the advantage of capturing all the nutrients, but still require processes to remove N & P before the waste nutrient solution is discharged. Costs are the highest of all options. Not all vegetables are suited to growing in this manner. Suited to high value crops with short storage life e.g., leafy salad vegetables. Finite life of system and waste will need disposal. Very high energy costs, but may result in reduction in the chemicals applied to control pests and diseases.
Crop Rotation (Improved management)	Some similar principles to catch cropping. Careful crop selection and timing is used to minimise the amount of excess N. Examples include the practice of growing a deep rooting, high biomass crop after a crop with a high nitrate leaching potential, e.g. a shallow rooting crop, or a crop that returns a large amount of N residues to the soil.	Not many studies have investigated targeted rotations to minimise leaching. Some reports from Denmark, China and New Zealand [19]. Should be combined with soil testing and fertiliser reduction to ensure that the subsequent crop utilises any residual N from the preceding crop. Cost is low. More optimised systems may be more profitable. Other factors such as market demand may make rotations difficult to implement. An example from Denmark showed that a deep-rooted cabbage crop could take up over 100 kg N/ha from between 1.0 and 2.5 m depth compared with a shallow-rooted leek crop that was unable to extract N from this depth. Unclear how widely used this is used in New Zealand vegetable production for N management, but already widely employed to minimise risks of disease carryover.

Technology Group – and subgroup	Description	Mitigation narrative
Soil/plant test-based approaches (Precision fertiliser management)	Use of soil and plant sensing or testing to inform nutrient decisions. Normally accompanied by some simple, to more complex, calculations of N requirements based on soil N availability or critical tissue N concentrations. Ideally used as part of nutrient planning systems and a decision support tool.	Rapid N tests provide grower with information on the soil N status. Plant tests provide information on plant status and should be used in conjunction with soil tests. New affordable plant sensors, including chlorophyll and canopy reflectance sensors, are promising new approaches for crop N status. These will require specific crop methods to be developed. Costs are relatively low for rapid N tests (approx. $NZ2–60 per test). Plant sensors will have one-off cost but low ongoing costs. Unclear how widely used this is used in New Zealand vegetable production [20,21].
Growing in soil undercover – runoff captured (New Technology)	This differs from the soil-less systems, as the vegetables are grown in soil under permanent or temporary cover. Runoff is captured from the fields under cover.	Requires skilled fertiliser and irrigation management to reduce leaching – losses are assumed to be low [22,23] (limited data). However, inefficiencies in both irrigation and nutrient management will lead to larger losses. Many soil-based glasshouse systems described in the scientific literature leached more N than uncovered systems, since high value crops were grown much more intensively to cover the high capital costs. Gowers tended to over-fertilise and over-irrigate to avoid losses in quality and yield. Costs are similar to the greenhouse systems described above. Need to renew soil periodically, or move cover to new location. Used in New Zealand for crops such as tomatoes, capsicums and cucumbers, but extent of use not known.
Constructed wetlands (Improved technology)	This is a remedial-type technology designed to reduce the concentration of nitrate in drainage water entering the wetland before it is discharged to waterways. Drainage water nitrate concentrations are reduced by microbial processes and plant uptake.	Widely researched and used worldwide [24,25]. Need a suitable area of land. Requires a drainage system to capture leachate and channel it into the wetland. Soil type is an important factor, with clayey soil types more suited to drainage systems that can capture leachate, and free draining sands are not suitable. High leaching losses could exceed the N-reducing capacity of the wetland, which would decrease its effectiveness. Large flow events can also reduce its effectiveness. Cost is moderate. Benefits include removal of P and sediment and increased biodiversity. Disadvantage is that wetlands may be a source of methane and nitrous oxide production. Rarely used in New Zealand vegetable production.
Bioreactors (Improved technology)	Similar to wetlands, this is a remedial-type technology designed to reduce the concentration of nitrate entering the bioreactor before discharging to waterways. Drainage water nitrate concentrations are reduced by microbial processes.	High leaching losses could exceed the N-reducing capacity of the reactor, which would decrease its effectiveness. High flow rates can also reduce its effectiveness. Effectiveness is expected to reduce over time (e.g. wood chip reactors, where woodchips may need replacing after several years). Cost: moderate but typically more expensive than wetlands. Can be some nitrous oxide production and some P release. Can also produce methane but this could be captured and used as biogas. Rarely used in New Zealand – examples are denitrification walls and woodchip bioreactors [26,27].

Technology Group – and subgroup	Description	Mitigation narrative
Mitigation effectiveness – Medium		
Soil-less cultivation of outdoor crops (New Technology)	In these systems, high value crops are grown outdoors in pots or other structures that are isolated from the soil using a range of growing media (inorganic, organic and synthetic). All runoff should be captured, stored and treated to remove N, e.g. using a bioreactor or other disposal system that does allow the run-off to enter waterways. Management is similar to that when growing under cover.	There is a lack of information on leaching from these systems. Based on the limited information, mitigation effectiveness may range between medium and high depending on the system's ability to capture and dispose of nutrients [28]. This system also avoids sediment losses. Leaching may occur where rainfall exceeds the storage capacity of the growing medium and is not captured by any run-off collection systems. Costs are relatively high for the setting up of growing media, structures and waste disposal. Not all vegetables are suited to growing in this manner. Best suited to low density planting. Waste material can be high in N, so needs treating, which is costly. Used in New Zealand for some strawberry and blueberry production. We are unsure of the extent.
Irrigation scheduling & soil moisture sensing (Improved water management)	Relevant to irrigated vegetable crops. Good management of irrigation reduces drainage, which in turn reduces nitrate leaching. Decisions are made based on plant water requirements, soil water availability, system delivery, rainfall and predicted rainfall. Deficit irrigation leaves room in the soil profile for rain that may fall. These practices reduce drainage.	Only relevant as a mitigation option where irrigation is required. Over-irrigation can lead to large leaching losses especially when there are large amounts of residual soil N. Poor irrigation can result in greater leaching losses than excess fertiliser applications. Large reductions in drainage can be achieved through irrigation scheduling based on sensing plant and/or soil and accurate models. A meta-analysis of agricultural crops showed that adjusting water application to crop requirements reduced leaching by 78% compared with over-watering practices. There are many examples of different soil moisture sensors used for scheduling irrigation in open-field vegetable crops. There are examples of reductions of 90% compared with non-scheduled irrigation (poor practice) in Florida for peppers, zucchini, squash and tomatoes [29,30]. Based on the information from these studies, we suggest that mitigation effectiveness may range between medium and high because the size of the effects is strongly influenced by the practice to which the mitigation is compared. Shallow rooting crops are most risky, as they have less ability to use water and take up N. Costs are relatively low but vary depending on the type of sensors, services and number of crops/paddocks monitored. Irrigation is widely used in New Zealand. There are many providers of soil moisture sensors and scheduling services. Other benefits: reduced N_2O emissions, improved water and nutrient use efficiency. Avoiding over-irrigating also reduces the risk of P and sediment runoff losses.
this id	These are grouped together and may be collectively called the three "R's". Right rate – applications are split into a series of smaller applications, minimising the amount of residual soil nitrate. Right time – applications are timed to match plant demand, minimising the amount of residual soil nitrate. Right place – fertiliser is applied adjacent to the plants and avoids N application to unproductive areas such as wheel-tracks and field edges, minimising the amount of residual soil nitrate across the paddock. These are key elements of good fertiliser management.	Widely proposed globally to mitigate nitrate leaching [31]. Leaching reductions from fertiliser are widely reported, including from New Zealand [32]. We suggest this has a moderate effect on leaching as it will reduce leaching of fertiliser N but does not affect the leachable N that is released from crop residues and mineralised soil organic matter. Cost is low and may be reduced when fertiliser is not applied. Some capital expenditure may be required for more advanced fertiliser application methods. Should be applied as part of best management practices. Easy, to more complex, to implement based on nutrient planning, soil and plant testing or sensing (see other Precision fertiliser management technologies). Should reduce N_2O emissions. Used in New Zealand, recommended as best practice but currently unknown how well or to what extent this is employed in the vegetable sector. Will form part of farm environmental management plans.

Technology Group – and subgroup	Description	Mitigation narrative
Fertigation (Precision fertiliser management)	Soluble fertiliser is applied in irrigation water. This is a form of precision fertiliser application (see Fertiliser - rates, timing and placement). Best fertigation practice is to apply amounts little and often, responding to plant requirements and soil supply, minimising the amount of residual soil nitrate. May also be applied from agricultural spray systems if no irrigation is used.	Widely used overseas [11]. Avoids large applications of solid fertiliser, which reduces the risk of nitrate leaching. Enables fertiliser to be applied at the right place, time and rate. Costs: Relatively low once irrigation is set up. Fertilisers designed for fertigation are typically more expensive as they need to be sufficiently soluble to flow through the irrigation or spray equipment. Also, there is a need for routine maintenance to clean pipes and irrigation emitters. Savings can be made where fertiliser use efficiency increases (kg product/kg fertiliser applied). Should be applied in conjunction with soil/plant testing or DSS tools to supplement soil supply. When used through irrigation systems this avoids the need for machinery traffic. Should be largely avoided when soil is wet to avoid drainage and leaching. Uniformity depends on the irrigation system but can be better than truck/tractor-applied fertiliser. Other benefits: reduced N_2O, reduced soil compaction – indirect benefits included reduced soil erosion, reduced fuel CO_2 emissions from fewer tractor passes required to apply fertiliser. Used and available in New Zealand. Extent of use is currently unknown, but several growers have reported using it. Expertise in design and application in New Zealand is limited.
Intercropping (Improved management)	Intercropping is the practice of growing two or more crops together to reduce the amount of mineralisable N at risk of leaching and drainage. This could be growing a deep rooting crop with a valuable shallow rooting crop. Alternatively, establishing a crop prior to the harvest of the first crop, to avoid a fallow period – which has a high risk of nitrate leaching.	Lack of information on N leaching reduction in vegetable production systems. Most research focused on management and yields. In a UK field trial of beans intercropped with wheat, intercropping was more profitable than beans alone and wheat was more profitable than beans. Residual soil N reduced from 40–120 kg N/ha with beans to 5–45 kg N/ha intercropped with wheat [33]. Costs: Low. Can potentially be more profitable with the optimum crop combinations. Also, there is the potential to reduce fertiliser costs where nutrient use efficiency is improved. Challenges are to find crops that fit together well. Often difficulties with planting, growth, harvesting and weed control. May be increased risk of crop failure with fewer herbicide options if weed infestations occur. Competition can result in yield depression.
Irrigation design (Improved water management)	Only relevant to irrigated vegetable crops. Improved irrigation systems provide water to the soil at the expected rate with low conveyance and application losses. Some more advanced technologies include variable rate irrigation that enable a grower to apply water at different rates and times to meet individual crop demands.	Widely researched and used globally [30,34]. Improved and more flexible irrigation designs allow growers to place the right amount of water at the right place at the right time. The key factor as to whether this is an effective mitigation is then whether the grower implements good practice to apply the right amount, at the right place and right time. Application rates should not exceed soil infiltration rates, as this drives runoff, erosion and leaching. Poor irrigation can result in greater leaching losses than excess fertiliser applications (see Irrigation scheduling & soil moisture sensing). Hence, this needs to be implemented with irrigation scheduling. Mitigation effectiveness may range between medium and high depending on the current practice with which it is compared. Irrigation design is less important than irrigation scheduling. Improved technologies include variable rate irrigation, drip and micro irrigation, centre pivot and fixed grid. Benefits include reduced N_2O emissions, improved water and nutrient use efficiency. Avoiding over-irrigating and changing to lower hourly water application rates can reduce the risk of P and sediment runoff losses. Irrigation is widely used in New Zealand, mainly in the drier eastern regions.
Residue management (Improved management)	Some vegetable crops leave residues that contain a large amount of N, which is at risk of leaching as they decompose. This approach reduces those losses by leaving the residues undisturbed rather than ploughing them in, or by removal of the residues for a useful purpose such as composting or anaerobic digestion.	This is important but only addresses one source on N leaching – crop residues, i.e. it does not address high soil N or over-fertilisation. Some field studies available. In a Dutch study, removal of broccoli residues reduced leaching by 35–60% [35]. Residues are important for retaining soil structure and some residues can be source of N, and other nutrients, for the following crop. Residue removal reduces N leaching for crops only where residues have low carbon:nitrogen (C:N) ratio. Leaving residues on the soil surface, as opposed to ploughing in, can reduce P and sediment runoff losses. May reduce N_2O emissions. Residue management needs to be part of a nutrient management plan.

Technology Group – and subgroup	Description	Mitigation narrative
Amendment (Incorporation of organic matter)	When amendments with a high C:N ratio, are mixed into the soil, soil mineral N is immobilised by microbial activity as these high C:N amendments are decomposed. Organic amendments with a high lignin or polyphenol content can slow the rate of N release into soils by mineralisation.	Few reported instances of this technology working well. Waste from the cardboard industry incorporated with sugar beet residue reduced leaching by one-third [35]. Very effective at immobilising N in the topsoil, but too difficult/expensive to incorporate at depth to immobilise N in the subsoil. May result in yield losses if too much organic matter is applied. Difficult to synchronise immobilisation and remobilisation of N within a cropping system. Will require more knowledge so ensure that a suitable rate is applied and no yield loss is incurred. Can prevent wood and cardboard wastes going to landfill. Can have beneficial effects on soil structure, which improves aeration and water-holding capacity.
Mitigation effectiveness – Low		
Maps or sensors followed by variable rate application (Precision fertiliser management)	Primarily focused on matching plant nutrient requirements with fertiliser applications. Yield maps and sensors can identify areas with high or low soil N concentrations. N fertiliser rates can be increased or reduced in these areas using variable rate application.	Used globally, but limited evidence of benefits for reduced leaching. Applies mainly to leaching directly related to fertiliser applications. May have some indirect benefits where fertiliser is not applied due to adequate soil supply. Most examples are for broadacre arable crops [36,37]. Lack of information on use in vegetable crops. Costs are moderate. Often services can be contracted in. Technology can be applied to tractors and fertiliser spreaders. Should reduce N_2O emissions. Used and available in New Zealand.
Fertiliser type (Precision fertiliser management)	Slow-release N fertilisers, or fertilisers containing inhibitors, can help to better match the supply of N to that required by the plant. Reduces the large peaks in soil nitrate concentration that arise from the use of traditional soluble fertilisers to reduce nitrate leaching.	Widely used globally [38]. Challenge is to match the release rate with the plant requirements. More challenging with short-rotation vegetable crops. Lack of evidence of effectiveness in reducing leaching from vegetable crops. Improving current practices using existing fertiliser will be of greater effectiveness. Costs are comparatively low and benefits low. Should reduce N_2O emissions. Used and available in New Zealand.
Plant growth regulators (Improved technology)	Applying plant growth regulators and reducing fertiliser inputs can produce plants with a lower N content. There was no reduction in yield, compared with those of fully fertilised plants. The reduced N fertiliser use is likely to result in less leaching.	Unclear on how widely used the technology is. Largely unproven technology, especially for vegetable production [39]. Lack of information for leaching mitigation. Focus of research has been more on plant growth. May improve nutrient use efficiency. Costs are low.
Urease inhibitors (Precision fertiliser management)	Urease inhibitors reduce the rate at which urea is converted to ammonium and the loss of ammonia gas.	Of limited use in vegetable production, as other forms of fertiliser (e.g. calcium ammonium nitrate, CAN) are more commonly used than urea to avoid associated scorching of the vegetable leaves. Cost is low and can be applied using existing machinery. As it reduces a loss of N, application should increase nitrogen use efficiency [40]. If this results in a reduction in fertiliser use, then leaching losses could be reduced. Avoids ammonia volatilisation losses and indirect losses of N_2O from deposited ammonia.

Technology Group – and subgroup	Description	Mitigation narrative
Zeolite (Amendment)	Clinoptilite zeolite is a porous mineral with narrow channels that absorb cations, with a high selectivity for potassium and ammonium. These channels are too narrow for nitrifying bacteria, so the absorbed ammonium is protected from being converted to nitrate. Specifically binds ammonium, so acts like a slow release N fertiliser.	Very limited information available. In an Iranian study, application of 9 t/ha of zeolite resulted in a 37% reduction in N leaching on a sandy loam soil [41]. Difficult to predict the rate of ammonium release from zeolite. If this is not accounted for and fertiliser is not reduced, there will be no reduction in leaching [42]. Cost: moderate. Large application rates of zeolite are required to exert the eff Other claimed benefits: improved soil structure, soil water-holding capacity. Also provides cation exchange capacity (CEC) which has been important in some international studies, but New Zealand horticultural soils have sufficient CEC.
Biochar (Amendment)	Biochar produced at high temperatures can develop nitrate-adsorbing capacity. Biochar addition can also affect soil hydrological properties (e.g. soil water-holding capacity), which can enhance or reduce nitrate leaching. Typically incorporated in soil.	Some limited evidence that biochar can reduce or slow the rate of nitrate leaching. Most of the work has been carried out using pot experiments. Evidence of nitrate binding by some biochars. Products vary widely owing to method of pyrolysis and fuel stock. Cost: moderate. Large rates are required. Other claimed benefits: improved soil structure, soil water-holding capacity and N_2O reduction. Also provides cation exchange capacity (CEC) which has been important in some international studies, but New Zealand horticultural soils generally have sufficient CEC. Used in New Zealand by at least one vegetable grower [43,44].
Nitrification inhibitors (Precision fertiliser management)	Nitrification inhibitors are chemicals that slow or stop the microbial conversion of ammonium to nitrate. Ammonium is bound much more strongly to the soil than nitrate, so is less easily leached. Commonly used inhibitors overseas: - 3,4-dimethylpyrazole phosphate (DMPP) -Dicyandiamide (DCD) - 2-chloro-6-(trichloromethyl) pyridine (Nitrapyrin)	Widely researched [45-48]. Many studies have shown reductions in nitrate leaching from fertiliser or urine patches. The mechanism requires that the inhibitor is at the site of the ammonium to prevent nitrification to nitrate. This requires a synchrony between the inhibitor and fertiliser or soil ammonium in time and place to be effective. Since most nitrate leaching is associated with soil mineralised organic matter and residues, the challenge is to apply the inhibitor at the right time and place in the soil to be effective. If applied to the fertiliser, the inhibitor will be close to the site of the fertiliser, having a localised effect on soil ammonium (NH_4) or urea. Nitrification inhibitors are also relatively short-lived in the soil. To be effective in reducing leaching from crop residue N or soil mineralised N, the inhibitor would need to be incorporated into the residues or soil. A potential risk is that the inhibitor delays the production of nitrate to a period when there is greater chance of leaching. Hence, we think it will have a relatively low mitigation effectiveness in vegetable cropping systems. DCD was widely used in New Zealand on pastures, but was discontinued because residues were found in milk. DCD is reasonably soluble and mobile. This mobility can mean DCD moves beyond the soil volume containing ammonium. DMPP available as coating of fertiliser (Entec®). The product is much more expensive than an uncoated fertiliser and DCD. Nitrapyrin does not reliably reduce nitrate leaching and can even increase leaching under some circumstances. It often increases ammonia volatilisation. Can move into adjacent waterways via spray drift through the air or in water runoff, where it can drive increases in toxic ammonia in aquatic systems and where it has a half-life of 4.4 years. DMPP (Entec®) is available in New Zealand. DCD was withdrawn by the fertiliser companies. Nitrapyrin is not available.

3.2 Most promising technologies

Our review of options highlighted that:

- There were no “silver bullet” technologies
- Most of the technologies are already available in New Zealand in some form
- High-cost technologies tended to have high potential for mitigation of nutrient losses, but their high costs mean that they are unsuited for large-scale, lower-value vegetable cropping
- There are a number of low-medium cost approaches and technologies that will minimise nutrient losses if applied well
- More integrated approaches have the greatest impact on reducing leaching
- The effectiveness of a number of the technologies will depend on specific environmental conditions (soil, climate) as well as crop and crop-rotation factors
- Combining some or all of these technologies will achieve best practice for minimising N leaching in vegetable cropping systems
- There are a number of approaches and technologies for which there is little information on their effectiveness to reduce nutrient leaching and we have not scored these as highly; most have been designed to improve production. In general, precision farming techniques have been slow in uptake [37]. Given improvements in sensing and computing access and capability, it is likely that this will become important in the future where these systems can optimise the amounts of nutrients applied to minimise nutrient losses
- Similarly, there is a large range of decision support tools produced globally and some in New Zealand. However, these overseas tools often have limited availability or applicability to New Zealand growers, and uptake of all decision support tools is limited
- There are some low-cost options that may have lower mitigation potential but are easily implemented, such as applying urea-based fertiliser with a urease-inhibitor
- In many of the studies we reviewed in our global scan, the comparison of the technology was often related to practices that we would not consider good practice in New Zealand, making it difficult to assess how well a technology will perform in New Zealand.

The promising technologies can be broadly grouped into:

- **Crop-based approaches** – which includes catch crops, intercropping and residue management
- **Optimising inputs** – includes irrigation scheduling, fertigation, soil/plant testing and fertiliser use
- **Remedial technologies** – wetlands and bioreactors
- **System optimisation** to minimise nutrient leaching. This includes both the preventative and remedial approaches, and encompasses nutrient management planning, decision support systems and precision farming techniques, irrigation system design, other integrated management systems and cropping rotation changes.

3.3 Most promising technologies: benefits and trade-offs

3.3.1 Crop-based approaches

Catch crops are one of the most promising technologies and are widely used globally to reduce nitrate leaching. Challenges include difficulties in sowing a catch crop if soils are wet (e.g. over winter), or when the period is too short to establish a crop. There is also uncertainty around the timing and amount of N released by the soil incorporated into the catch crop, which may cause growers to err on the side of caution and apply excess N to the following crop.

Potential benefits include: (i) reduced risk of erosion, P run-off and sedimentation due to crop-cover and reduction of soil water content; (ii) improved soil quality; and, (iii) reduced N_2O emissions. One small environmental trade-off is increased CO_2 emissions from extra tractor work to establish and then incorporate the crop.

Intercropping can spread financial risk, as two crops are grown together. However, they are much more difficult to manage, e.g. having two crop types reduces options for spraying, and creates challenges for harvesting with two crops likely to have different harvest dates.

One of the challenges with crop-based approaches is the **management of residue** N following harvest. Incorporated crop residues can be a large source of N leaching, and risks can be quite high if the crop is harvested in winter when the growth of the following catch crop will be slow, or maybe difficult to establish. Rather than incorporating residues, these may be removed and digested for biogas, or sold as animal feed. A trade-off with removing residues is that this also removes other nutrients besides N, and removes the organic matter, which is beneficial to soil structure if returned to the soil. Leaving the residues standing in the field, rather than ploughing them in, can reduce N leaching, but this may create a reservoir for plant diseases.

3.3.2 Optimising inputs

Irrigation systems must apply the right amount of water at the right rate to the right place to reduce the risk of drainage and runoff. There are no known drawbacks to improving irrigation systems, apart from one grower mentioning that the new computer-driven variable rate irrigator was less reliable than his older, simpler system. Drip tape is more water-efficient for bedded crops than sprinkler irrigation, since this reduces water application to unproductive areas like wheel tracks, but it is much more costly and produces plastic waste when the tapes require disposal.

Benefits of improved irrigation management **using scheduling and sensors** include: increased water and nutrient use efficiency; reduction in N_2O emissions, improved crop yield and quality, reduced risk of soil compaction, erosion, P run-off and sedimentation due to reduction of soil water content.

Benefits of including **fertigation** into an existing irrigation system include: improved nutrient use efficiency, reduction in diesel costs and CO_2 emissions of applying fertiliser via tractor, and potential to reduce N_2O emissions, and a reduced risk of soil compaction compared with machine-spread fertiliser.

Soil testing for is highly cost-effective, with per test costs for nitrate ranging from $2 for a quick test to $60 for a commercial laboratory test, plus approximately 30 minutes of labour to collect the soil, and then the cost is spread over several hectares. Soil sampling below 30 cm is also informative for nitrate leaching management, but takes considerably more time. Soil testing for P typically requires less frequent testing but is important to avoid applying excess fertiliser to crops. Excess P fertiliser application increases the risk of P run-off, and increases the amount of P lost if sediment runoff occurs.

Applying the right rate of **fertiliser** at the right amount and the right time minimises the amount of mineral N (or P) required in the soil. Benefits of this are improved nutrient use efficiency, improved crop quality and reduced risk of N_2O emissions. There are potential trade-offs where there are more frequent fertiliser applications that increase CO_2 fuel emissions, increased compaction and, if this is the case, increased risk of erosion.

3.3.3 System optimisation

Perhaps the biggest challenge for **system changes and optimisation** is the requirement of a high degree of understanding of the crop-soil system. Skilled agronomists and growers are able to do this, but often the use of decision support systems is helpful. Simple apps are available to optimise parts of the system, e.g. the Quick Test Mass Balance Calculator [49] for calculating crop N requirements. One of the biggest challenge for growers will be to find suitable decision support tools to help their management. There is a need for more integrated system tools that are smart and simple enough for growers to use. For some crops no decision support systems are available, or those that do exist have limited ability to predict N leaching accurately.

Crop rotations to mitigate N leaching include practices such as following a shallow-rooting crop with a deep-rooting crop, or replacing a crop with a high N leaching potential with one with a lower N leaching potential during winter. These may incur some opportunity cost.

3.3.4 Remedial technologies

Wetlands and **bioreactors** are remedial-type technologies and are designed to process up to a maximum N load over a certain time, which may be exceeded if large drainage events have high N concentrations. They should be considered complementary to best practice, rather than the sole answer to N leaching. Constructed wetlands and bioreactors require soils that are suitable to a drainage system, so that the leachate may be captured.

Benefits may include: production of biogas from enclosed bioreactor systems, increased biodiversity for wetland areas, sediment and P capture in biomass in specially designed wetlands. The P will still need to be removed and disposed of, but can potentially be recycled.

Trade-offs from both wetlands and bioreactors include: release of methane and N_2O, and P release has been found from bioreactors.

3.4 Most promising technologies: challenges with implementation

As we have noted above, many of the technologies are available and used to some extent in New Zealand. We are not aware of any work that has quantified the uptake of the various technologies and approaches, or assessed how successfully they have been implemented, to mitigate nitrate leaching losses. Conversely, there is limited understanding of what the actual contribution of current practices is to nitrate leaching, i.e. the ability to link specific management to leaching losses. Our global literature scan does give some indication where improvements can be made, assuming these practices are not being implemented in New Zealand. For growers to adopt new mitigation technologies or approaches, evidence of benefit in New Zealand systems is likely to be important.

One of the largest challenges faced by growers is how to deal with the complexity of the crop-soil-climate system interactions, let alone other business and regulatory imperatives. Specialised knowledge is required to understand the various trade-offs between management decisions. Hence the availability of knowledge, and accessible and appropriate tools to achieve best practice mitigation, is crucial.

Given the dynamic nature of the biophysical systems, the grower will need flexible and adaptable systems to be able to react to changeable weather and to adapt nutrient plans within growing seasons. Similarly to the need to adapt to temporal changes, the grower needs to be able to adapt to spatial variability of the land. Hence, it is important that we better understand the relative importance and complexity of these factors, so that the best mitigation technologies and approaches can be tailored to the growing system.

While there are many decision support tools, sensors and precision agriculture technologies available worldwide, reportedly uptake still remains poor, and sensors and computer-based systems are not often well integrated. There are also a number of decision support tools developed in New Zealand for vegetable growers, but we do not know how well and how widely they are used. Traditionally, New Zealand tools have been developed because overseas tools are not suited to our conditions (soil, crop, climate specific); many of those available overseas remain country specific and are not readily transferable.

The cost of implementation will be important for many growers, and demonstration of benefits and trade-offs is also likely to be important.

4 Recommendations and next steps

Our recommendations for the most promising mitigation approaches identified from the global literature scan are:

For field crops (i.e. not suited to, or uneconomic, for covered systems):

- More integrated management and system optimisation of crops, nutrient and water (best management) (Section 3.3.3), to maximise the potential reduction in nutrient leaching and runoff losses. Expertise, skills, increased grower education and decision support tools are needed
- Optimised catch crops and crop rotations, to ensure fallow periods are minimised and there are crops to capture excess nutrients in the soil profiles (Sections 3.3.1 and 3.3.3). This approach has the added benefit of reducing erosion risk (sediment and P losses) by ensuring there is plant cover while the catch crop is grown, and maintaining soil quality by cultivating in that plant material at the end of the cover crop
- Nutrient management plans and tools (including soil testing) to reduce fertiliser inputs and manage soil nutrients, including management of residues (Sections 3.3.1 and 3.3.2)
- Irrigation scheduling, including plant/soil sensing, to avoid drainage losses (Section 3.3.2).
- Fertigation, where irrigation design or equipment allows (Section 3.3.2)
- Constructed wetland and bioreactors (Section 3.3.4), to remove nutrients where the nutrient losses can be captured from the paddocks (e.g. surface- or field-drained systems, or from drainage from covered growing systems).

For crops of high value that may be economically grown under cover:

- Greenhouses with soil-less growing media, for some types of high value crops where the waste nutrients can be captured and removed (Section 3.3.4)
- Vertical farming for high value crops, acknowledging that these options have large energy requirements.

Future opportunities:

- Precision farming using sensing and variable fertiliser and irrigation. These options may be effective in crop-soil systems with large variability.

Low-cost technologies that provide some benefit:

- Using urease inhibitors with urea-based fertiliser, although this may create associated practical issues in terms of the timing of N release matching the demands of the crop.

4.1 Addressing knowledge gaps in New Zealand

Based on the global scan, we identified large gaps in our knowledge of what is current, good or best practice, and what the expected nutrient losses are for vegetable crops. As highlighted above regarding growers' challenges with implementation (Section 3.4), we do not have a good understanding of how many mitigation technologies and approaches are in use and under what conditions they are implemented, to gauge the mitigation opportunities. Equally, we do not presently understand the barriers to use and implementation in their cropping systems.

Simply put, what are current practices for New Zealand vegetable growers? What technologies are they using? And are all the methods and technologies in use being used optimally? It would also be good to understand what changes they have been making to reduce their impact. One of the challenges is to understand how much the water quality issues associated with vegetable growers are due to current versus legacy practices – particularly as there is an expectation that practices have been improving.

Our recommendations for next steps are based on addressing some of these gaps:

- Firstly, it is critically important to understand the range of technologies and approaches currently being used, and how they are being used. We recommend survey-type approaches with growers to address this knowledge gap. Is best practice being followed?
- Secondly, we must address the large gap in our understanding of the barriers to adoption of mitigation approaches. The 'Sustainable Vegetable Systems' programme, funded by MPI and the vegetable industries, might partially address this with a social science-based review of grower attitudes and behaviours. This work is currently underway
- Thirdly, we should undertake whole-system modelling approaches to understand the opportunities for technologies to mitigate leaching using process-based system models. For example, crop rotations – including different crop types, rotation mixes, inclusion of catch crops, intercropping, fertiliser timing, removal and incorporation of residues, irrigation management – can all be simulated for different soil types and climates, and leaching predicted
- Fourthly, it is important to to investigate the growers' need for user-friendly tool(s) that would help to manage their complex nutrient, water and crop requirements. Lessons should be learned from both overseas and New Zealand experiences. Tools for nutrient management are often different from those for accounting or reporting, and thus it is critical that management tools are designed with growers for growers. Assuming a tool(s) are developed, these will need to be tested to ensure growers are confident in the accuracy of the tool
- Not one of these exercises is trivial in terms of resources and time. The first steps require specific expertise in working with growers to understand their practices, and their drivers to change practices and systems. Modelling the crop system and simulating practices and technologies is a powerful approach to understand where best to target changes in cropping systems.

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