Mitigating the leaching of nitrate from stony soils on the Waimea Plains: literature review

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Mitigating the leaching of nitrate from stony soils on the Waimea Plains: literature review

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Hadee Thompson-Morrison, Jo Cavanagh

Manaaki Whenua – Landcare Research

Reviewed by:	*Approved for release by:*
John Drewry Senior Researcher Manaaki Whenua – Landcare Research	Graham Sevicke-Jones General Manager – Science Knowledge and Translation Manaaki Whenua – Landcare Research
Ardi Ash Senior Resource Scientist – Land & Soil Tasman District Council	

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Summary

Project and client

- Ranzau soils on the Waimea Plains, Tasman District, are widely used for various horticultural crops but are highly susceptible to nitrate leaching due to their stoniness and low water-holding capacity.
- Tasman District Council contracted Manaaki Whenua – Landcare Research to conduct a literature review of the efficacy of soil amendments to reduce nitrate leaching from these soils.
- The work was carried out from July to November 2024 under Envirolink small advice grant 2502-TSDC196.

Objectives

- To complete a literature review of the efficacy of soil amendments to reduce nitrate leaching in a New Zealand context, and consider any barriers (e.g. technological, economic, environmental) and co-benefits (e.g. reductions in nitrous oxide emissions, soil carbon sequestration).

Methods

- Relevant literature for the review was identified using Google Scholar to search for articles on the effect of biochar, compost, straw, crop residues, sawdust, and green manure on nitrate leaching from soils.
- A high-level assessment of the associated barriers and co-benefits was also undertaken through expert assessment.

Results and conclusions

- Several factors intersect to influence nitrate leaching from soils. Where nutrient additions exceed plant requirements, and there is a transport pathway with limited attenuation of nutrients, the risk of negative impact on groundwater quality increases due to the potential for transfer of nitrate to drainage. The attenuation potential of soils will depend on soil properties such as depth and texture, which influence the time available for attenuation processes to occur. There is a very fine balance between nitrogen availability and plant nitrogen demand in achieving the desired production levels.
- A meta-analysis showed an overall reduction of 13% in nitrate leaching from soils amended with biochar (n = 120). However, the efficacy of this varied with soil and biochar properties, and farm management. Biochar had additional benefits when used as a soil amendment, including short-term reductions in nitrous oxide emissions and increased cation and anion exchange capacity.
- Organic amendments (including compost, sawdust, crop residues, and straw) were reported to be effective at reducing nitrate leaching from cropping soils. Differences in the functioning of these amendments relate to their varying initial carbon:nitrogen ratios and therefore their differing rates of organic matter mineralisation.

- Green manures, or crops grown at the end of a rotation and incorporated into soils, have been variously reported as increasing and decreasing nitrate concentrations in soils. These differing results are attributed to differences in climate and soil texture in the regions of the studies. Additional benefits of green manures include increased soil microbial carbon and soil enzyme activity.
- Potential co-benefits to the use of biochar and other organic amendments in cropping systems relate to diverting waste streams to productive use. Diversion of waste streams that are currently burnt has the potential to improve air quality and reduce air pollution.
- Potential barriers to the use of organic amendments include the cost of amendments (unless waste products are supplied free), the variable quality and characteristics of amendments, the longevity of amendments in soils, and the knowledge required on the efficacy of amendments to sorb nitrate while maintaining sufficient nitrogen to meet plant demand.
- A substantial potential barrier to the efficiency of organic amendments to reduce nitrate leaching relates to the potential site-specific increase in attenuation potential produced by the addition of amendments. This consideration feeds into decisions on suitable land use. Ranzau soils are coarse textured, shallow and free draining, so they may not be inherently suitability for intensive cropping given the resulting high nitrate leaching if high nitrogen inputs are applied. Also, the limited incorporation depth of these soils may limit the ability of any amendment to attenuate nitrate before drainage reaches groundwater.

Recommendations

- Given the shallow depth of Ranzau soils, it is critical to develop a thorough understanding of nitrogen cycling in these cropping systems, and the relationship of this cycling to management practices (including irrigation and fertiliser applications for the specific crops being grown), in order to better quantify the potential benefits of soil amendments to minimise nitrate leaching.

1 Introduction

The Waimea Plains in the Tasman region are widely used for various horticultural crops, including fruit, vegetables, and boutique crops such as hops and grapes. However, its eastern portion, covering about 1,600 ha, is dominated by a distinctive stony soil type, called Ranzau. These soils are predominantly free-draining and shallow, with an average depth to gravel of 22 cm. Ranzau soils are distinguished by their surface and sub-surface stoniness, with some topsoils containing more than 75% stones (Campbell 2016).

These soils are highly susceptible to nitrate leaching due to their stoniness and low water-holding capacity, and nitrate leaching is suggested to be one of the main sources of elevated nitrate levels in underlying aquifers. Potential mitigation strategies, including limiting fertiliser input and improving irrigation efficiency, are being investigated, but the use of soil amendments is not. Tasman District Council is seeking a literature review of the efficacy of soil amendments to increase soil organic matter and reduce nitrate leaching from these soils.

Manaaki Whenua – Landcare Research was contracted to undertake this review under Envirolink Grant 2502-TSDC196.

2 Objective

To complete a literature review of the efficacy of soil amendments to reduce nitrate leaching, in a New Zealand context, and consider the barriers (e.g. technological, economic, environmental) and co-benefits (e.g. carbon soil sequestration).

3 Methods

Relevant literature for review was identified using keyword literature searches of Google Scholar: 'soil organic carbon', 'water-holding capacity', 'nitrate leaching' + 'biochar', 'compost', 'sawdust', 'straw', and 'green manure'. Preference was given to reviews and meta-analysis articles for further review rather than extensive numbers of individual studies, given the limited time available for this work.

However, where identified, individual studies on the use of organic amendments to reduce nitrate in New Zealand, or specifically on cropping soils, were reviewed. A high-level assessment of the associated barriers and co-benefits was also undertaken by the authors.

4 Results

4.1 Factors influencing nitrate leaching

Several factors intersect to influence nitrate leaching from soils. Where nutrient additions (e.g. nitrogen fertiliser applications) exceed plant requirements, and there is a transport pathway with limited attenuation of nutrients, the risk of a negative impact on groundwater quality increases due to the potential for transfer of nitrate to drainage (McDowell et al. 2019). These principles are captured by the Ministry for the Environment's (2024) risk index tool for estimating the risk of farm-level nitrogen loss (Figure 1), in terms of source, transport, and modifier (or mitigation).

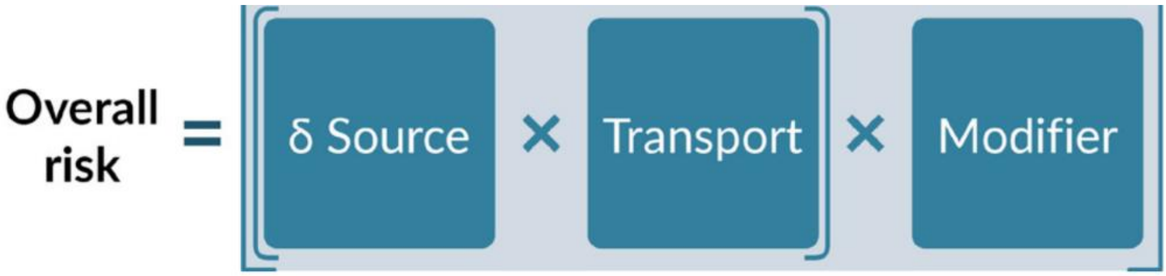

Figure 1. Risk index tool for nitrogen leaching loss (Ministry for the Environment 2024).

Reid and Morton (2019, p. 19) summarise the point well:

> Nitrate leaching occurs when drainage follows rainfall or irrigation. It is greatest if nitrate-N has been released from the breakdown of soil organic matter, or added from fertiliser, faster than the crop can take it up. Usually the risk is greatest between late autumn and early spring, or if irrigation is excessive during crop growth.

These findings are supported by a fluxmeter study by Norris et al. (2018, 2023), where high net losses were associated with high drainage volumes and high inorganic nitrogen concentrations (predominantly nitrate) in drainage water. The highest drainage losses occurred from late autumn to the early spring months when rainfall and soil moisture contents were highest.

Figure 2. summarises nitrogen cycling and the processes leading to nitrate leaching from soils. The attenuation potential of soils will depend on soil properties, including depth and texture, because this influences the time available for attenuation processes to occur. There is a need to achieve a very fine balance between nitrogen availability and plant nitrogen demand to achieve the desired production levels while minimising losses to the environment.

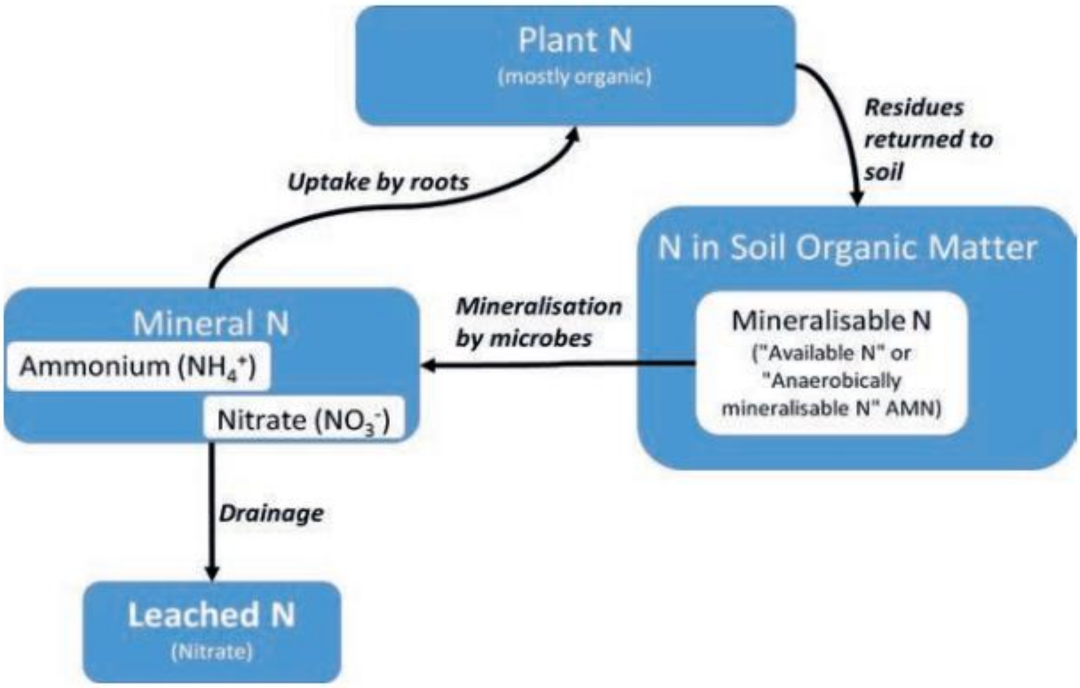

Figure 3. Nitrogen cycling in soils and processes resulting in leaching of nitrate.
(Source: Reid & Morton 2019)

4.2 Soil amendments to minimise nitrate leaching

Various organic soil amendments such as compost, biochar, and crop residue have the potential to minimise nitrate leaching from topsoil through different mechanisms. These include increasing the water-holding capacity of soils (and thereby reducing drainage), sorbing excess nitrate, and offsetting the addition of inorganic fertiliser.

4.2.1 Increasing water-holding capacity

The addition of organic amendments can increase the water-holding capacity of soils through improvements in soil structure, increased porosity, and organic matter content. Water retention in soils is facilitated by organic matter (Lal 2020), with a 1% organic matter increase claimed to increase the water-holding capacity of soils by 160 m^3/ha (Envirofert 2024). Amendments such as biochar can increase the specific surface area of soils and increase the formation of functional groups that facilitate water retention (Huang et al. 2021).

Increasing the water retention of soils results in less drainage and provides more time for nutrients in drainage water to attenuate before they are leached through soils. This can also provide soil water reserves for plants, improving the growing conditions (Brunton & Wadani 2021). However, the significance of increased water-holding capacity will depend on the water flux of a particular site. For example, increasing the water-holding capacity of shallow soils in areas with high rainfall or irrigation rates may not prevent substantial drainage volumes.

4.2.2 Sorbing excess nitrate

Organic materials in soils may sorb excess nitrate, particularly amendments with high carbon:nitrogen ratios such as biochar and sawdust. Nitrate may then be slowly released back to plants (Hagerman et al. 2017). Biochars or composts with relatively high carbon concentrations tend to release nitrates more slowly, while amendments with lower carbon concentrations will release nitrates more rapidly (Hagerman et al. 2017). This release of nitrate can align with plant demand, but a sharp focus on fertiliser application is required to match applications to plant requirements and reduce the concentrations of excess nitrate.

4.2.3 Offsetting inorganic fertiliser additions

Organic matter added through amendments can decompose, releasing inorganic nutrients and making them available for plants (particularly nitrogen and phosphorus). This provides the ability to offset fertiliser additions (i.e. reduce fertiliser input). However, a good understanding of the potential nutrient release from organic matter is needed in order to efficiently manage plant demand, particularly in the context of horticultural production. Nitrogen release from organic matter can be measured as potentially mineralisable nitrogen, but the actual mineralisation within a particular soil will vary with soil and climate conditions (Beare et al. 2022).

4.2.4 Green manure and catch crops to capture excess nitrogen

Green manures and catch crops are crops grown at the end of a cropping rotation to capture and utilise excess nitrate in soils. Catch crops are harvested and removed, while green manure crops are incorporated into the soil while they are still green. In this way, green manure uses or takes up excess nitrate and supplies organic matter to soils.

4.2.5 Organic amendment properties

Although the properties of organic amendments can be generalised (e.g. biochar contains high carbon), there can be broad variation in the properties of these products. This can depend on the feedstock and processes used to produce the amendments. In general, the properties of compost and straw are more consistent than those of biochar, which can be produced using different types of equipment and feedstock, with varying levels of controls (Siedt et al. 2021).

The degree to which organic amendments are effective at mitigating nitrate leaching through the above mechanisms will depend, in part, on the properties of those amendments. The carbon and nitrogen concentrations as well as the carbon:nitrogen ratio will influence the rates and amounts of organic matter mineralisation. Generally a lower carbon:nitrogen ratio indicates more rapid mineralisation (Heuck & Spohn 2016). While the properties of amendments are variable and will depend on the feedstock, the carbon:nitrogen ratios of different amendments would typically be highest in biochar and sawdust, followed by straw, crop residues, and lowest in compost. Amendments that contain higher total nitrogen concentrations will increase soil nitrogen concentrations, which, if mineralised and not used by plants, may result in leached nitrate.

Thus there is a need to understand the nitrogen flux, including the plant demand and supply, of the cropping system and to match inputs to plant demands (Beare et al. 2022).

4.3 Biochar

A meta-analysis covering 88 peer-reviewed publications with 608 observations by Borchard et al. (2019) showed an overall reduction of 13% in nitrate leaching from soils amended with biochar (n = 120). However, the efficacy of reduced leaching varied with soil and biochar properties and farm management. This meta-analysis of nitrate loss reductions due to biochar applications revealed that studies that ran for over 30 days showed consistent reductions of 26 to 32%. Nitrate loss reductions were greatest in fine-textured soils, and biochar did not reduce nitrate leaching in sandy soils. Biochar amendments were also shown not to reduce nitrate leaching (or nitrous oxide emissions (n = 435) in perennial or grassland systems. Therefore, any potential use of biochar on the Waimea Plains should consider the type of crop and farming system.

The pH and feedstock of applied biochar influenced nitrate leaching, with acidic to neutral (pH < 7.8) and strongly alkaline (pH > 9.6) biochars reducing nitrate leaching. Conversely, wood biochars with a pH between 7.8 and 8.9 increased the concentration of nitrate in soils. A carbon content of <78%, nitrogen content of 0.33–5.9% and a carbon:nitrogen ratio of 100–200 in the biochar applied also reduced leaching of nitrate from soils. Higher application rates (>10–20 t/ha) were more effective at reducing nitrate leaching and nitrous oxide emissions from soils.

Borchard et al. (2019) report reductions in nitrous oxide emissions from arable and horticultural systems (excluding perennial crops) with applications of biochar. However, these reductions tend to become negligible 1 year after application. As the majority of nitrous oxide emissions from New Zealand's soils tend to come from intensive beef and dairy soils (specifically from urine patches), the nitrous oxide mitigation potential of biochar is likely to be of less interest in the current context.

Other benefits of biochar include increasing soil porosity and surface area, which can increase water-holding capacity and improve root penetration through decreasing tensile strength (Knowles et al. 2011). Also, biochar can increase the cation and anion exchange capacity of soils (Knowles et al. 2011).

4.4 Organic amendments

Composts, straw/crop residues, sawdust, and green manure have similar mechanisms relating to nitrate leaching mitigation. The fundamental difference in their functioning relates to their differing carbon:nitrogen ratios and therefore their differing rates of mineralisation (see section 4.2.5).

4.4.1 Compost

As with biochar, the effects of applied compost on soil properties and nitrate leaching are dependent on multiple factors, including soil type, application rate, and compost production processes (Lim et al. 2018; Siedt et al. 2021). In a review of the efficacy of organic amendments in reducing nutrient losses from soils, Siedt et al. (2021) found that compost with a carbon:nitrogen ratio >20 can result in nitrogen immobilisation in soils, and that nitrate leaching is negatively correlated with the carbon:nitrogen ratio of compost. However, a high nitrogen concentration in compost can amplify the risk of nitrate leaching, essentially acting as a source of nutrients that may exceed plant requirements (Lim et al. 2018). Therefore, the use of composts with low nutrient (nitrogen) concentrations may be more beneficial for Ranzau soils.

Compost additions have also been reported to improve the soil physical structure of both clayey and sandy soils, and increase infiltration and permeability (Leogrande et al. 2014; Siedt et al. 2021). A trial conducted in Australia demonstrated a correlation between the water retention of soils and the compost application rate (tested at 0, 10, and 20 wet tonnes per hectare [wt/ha]), and applying compost at a rate of 20 wt/ha significantly increased water-holding capacity from control conditions (Brunton & Wadani 2021). Composts may also decrease nitrous oxide emissions from soils (Lim et al. 2018).

4.4.2 Sawdust

Few references were found on the efficacy of sawdust as a soil amendment at reducing nitrate leaching from soils. However, the use of sawdust in constructed 'denitrification barriers', whereby a solid carbon-rich substrate is constructed within the flow path to water sources, has been trialled as a biotechnology (Schipper et al. 2010; Bednarek et al. 2014). Sawdust was found to be a long-lasting material, able to provide daily nitrate removal of 0.7–2.6 mg/L/day over 15 years, when denitrification barriers were constructed with a sawdust content of 15–20% (Bednarek et al. 2014). This suggests sawdust has some potential to mitigate nitrate leaching from soils.

4.4.3 Crop residue/straw

Siedt et al. (2021) conducted a review of organic amendments used for soil improvement, and found that incorporating straw into soils immobilised mineral nitrogen, leading to a reduction in nitrate leaching. Siedt et al. (2021) also found that straw and crop residues incorporated into soils increased soil organic carbon stocks and increased the water-holding capacity of soils.

A meta-analysis of crop residue impacts on nitrogen cycling, covering 90 studies and 345 observations, found that incorporating crop residues into soils significantly decreased nitrate leaching by 14% (Li et al. 2021). This decrease was highest in loamy soils. Conversely, incorporation of crop residues significantly increased nitrous oxide emissions by 30% on average. This increase was significantly negatively correlated with mean annual temperature and precipitation; i.e. nitrous oxide emissions increased as temperature and rainfall decreased from sub-tropical to temperate conditions. This increase was most pronounced in soils with a pH between 5.5 and 6.5, or above pH 7.5 if the clay content was low.

4.5 Green manure

Green manure, or crops grown at the end of a rotation and incorporated into soils, have been reported to reduce nitrate leaching. A global meta-analysis of the effects of cover crops on nitrate leaching (1,119 observations from 41 articles) reported that cover crops reduced leaching by 69% compared with soils left fallow (Nouri et al. 2022). The greatest decrease was seen with brassica and grass species (75% and 52% reductions, respectively), with Ultisols (Ultic and Granular Soils), Histosols (Organic Soils), and Inceptisols (Brown, Gley, Pallic, and Recent Soils) showing the greatest decrease in nitrate leaching (77%, 78%, and 77%, respectively).

The authors concluded that soils with a higher sand content benefited more from cover crops in terms of reduced nitrate leaching, and that vegetable production systems benefited more than field crops (roughly equivalent to arable crops). This difference between vegetable and field crops was suggested to be attributable to vegetable crops being grown on sandy soils, and/or the less extensive root systems of vegetable crops, which could leave behind more residual nitrate in unexplored portions of the soil profile.

Green manure has been variously reported as reducing and increasing nitrate concentrations in soils. A 1-year field trial assessing the efficacy of legumes as green manure found lowered concentrations of nitrate in soils with green manure crops grown (Li et al. 2015). A meta-analysis covering 67 field experiments in Argentina found that both legume and non-legume cover crops (including green manure applications) decreased nitrate in soils (Alvarez et al. 2017). In both of these meta-analyses the decrease in nitrate concentrations was inferred to result in lower amounts of nitrate leaching, but leaching was not directly assessed.

Conversely, a meta-analysis of studies from China that included data from 104 studies and 2,955 observations found a mean increase in nitrate concentrations in soils using green manure, and this was significantly greater using legume species (65% increase in 0–20 cm) than non-legume species (11% increase in 0–20 cm; Ma et al. 2021). The authors attributed the discrepancy between their results and those of other studies (such as those mentioned above) to differences in climate and soil texture in the regions of the studies.

Additional reported benefits of green manure include increased soil microbial carbon and soil enzyme activity. In their meta-analysis, Ma et al. (2021) reported mean increases in soil microbial carbon of 28% and in soil enzyme activity of up to 39% in green manure treatments.

4.6 New Zealand studies

The majority of New Zealand studies on reducing nitrate losses have been done in the context of grazing systems (or mixed cropping systems that include grazing), due to the greater focus on nitrate loss under pasture relative to cropping. A Google Scholar search for New Zealand-specific studies on organic amendments and nitrate leaching in cropping systems returned zero relevant results from a selection of studies.

4.7 Site-specific factors influencing the efficacy of nitrate leaching mitigation

A final consideration in relation to the efficacy of organic amendments to reduce nitrate leaching in Ranzau soils is the nature of these soils. The Ranzau soils are stony, coarse, shallow (average depth to gravel of 22 cm) and free draining (Campbell 2016), which will limit the ability of any amendment to attenuate nitrate before drainage reaches groundwater. Further, any cultivation to enable the incorporation of the amendments may exacerbate nitrate leaching. Deeper soils may provide a better opportunity for organic amendments to effectively attenuate nitrates before they drain to groundwater. Broader consideration of the potential for, and planning of, land-use change to reduce the environmental challenges associated with agriculture may need to be considered (Parliamentary Commissioner for the Environment 2024).

4.8 Barriers and co-benefits

Potential co-benefits to the use of biochar and other organic amendments in cropping systems (excluding those relating to soil quality parameters, discussed briefly in sections 4.3 and 4.4) relate to diverting waste streams to productive use. The application of compost, sawdust, straw, and crop residues to land converts waste products that may otherwise be burnt or disposed of in landfill to soil conditioners that add value to production. The diversion of waste streams that are currently burnt has the potential to improve air quality and reduce air pollution (Jones 2023). Similarly, green waste streams can be converted into biochar to be used as a soil conditioner.

The use of waste products may incur less cost than commercially available amendments, particularly if they can be supplied free. However, the production of biochar requires specialist equipment and is costly when producing small quantities. Sourcing biochar may be a potential barrier to its use due to a lack of consistent local sources.

The quality and characteristics of amendments are variable (see section 4.2.5). A good understanding of the characteristics of amendments would be required, particularly for composts and biochars, which may vary depending on the feedstocks and, for biochar, the controls used during the production process. Sawdust should be sourced from untreated wood to avoid introducing contaminants from timber treatments to soils. Currently there are no requirements to characterise biochars in New Zealand, so any biochar used to mitigate nitrate leaching should be tested to confirm its ability to sorb nitrate.

Conversely, there may be yield penalties if nitrate sorption by biochars or other amendments removes nutrients required by plants, with one study reporting a reduction in crop yields in biochar treatments compared to controls, attributed to nitrogen deficiency (Haider et al. 2017). Other amendments may also result in reduced yields, with a New Zealand study reporting that crop residues incorporated into soils in a mixed-cropping system resulted in yield penalties of 20–30% due to nitrogen immobilisation during residue decomposition (Francis et al. 1994).

Thorough knowledge of the specific amendments used – including their efficacy to sorb nitrate while maintaining sufficient nitrogen to meet plant demand, and their longevity in soils – is required to ensure any potential applications are effective and well managed. This includes land management practices that influence amendment stability and longevity.

Biochar and other amendments can be broken down through physical soil disturbance typical in cropping systems, including ploughing and tillage. This disturbance can act in the same way as natural weathering, decreasing particle size and increasing the mobility of smaller particles. The breakdown of biochar (and other amendments) may also be accelerated through root disturbance during regular cultivation (Joseph & Taylor 2024). The effect of land management processes can be substantial enough to over-ride competing soil processes that act to protect biochars in soils (Wang et al. 2022).

4.9 Best soil management practices for sustainable vegetable production

There are several management practices that should be employed in vegetable cropping systems to reduce negative environmental impacts (including nitrate leaching), in addition to the potential use of organic amendments and maintenance of soil organic matter discussed in this report. As mentioned in section 4.1, there is a need to understand and maintain the fine balance between nitrogen availability and plant nitrogen demand to achieve the desired production levels while minimising losses to the environment. This involves optimising nitrogen and irrigation management in terms of timing and application rates to match plant requirements.

Using available water deficits to schedule irrigation timing has been shown to reduce nitrate leaching from vegetable systems (Sexton et al. 1996). Irrigation amounts should not exceed the soil's water-holding capacity and induce drainage. Excess irrigation should not follow fertiliser applications (Reid & Morton 2019). Further relevant information is outlined by Reid and Morton (2019), who provide industry guidance on nitrogen management, including:

- determining the soil's need for nutrients through soil and plant tissue testing, use of nutrient budgets, and having a working understanding of the principles underlying fertiliser use
- applying fertiliser to achieve an identified crop response, rather than as a 'routine' procedure
- matching nitrogen applications to plant requirements and crop-specific rates of uptake, splitting applications to match plant requirements with supply, and avoiding applications at times when rain is forecast or when soil temperatures are low enough to inhibit plant growth, as this is likely to lead to nutrient losses from soils

As mentioned above, however, the suitability of specific soils for intensive land uses should be considered within the bounds of best management practices for intensive production: modelling undertaken for Horticulture New Zealand (2024) showed that reducing typical nitrogen fertiliser application rates to match best practice industry recommendations for lettuces and onions on Ranzau soils would still result in very high nitrate losses, exceeding 100 kg N/ha/yr.

Several cultivation-related practices are generally recommended for vegetable production systems. Reducing tillage and soil disturbance associated with cultivation can reduce the potential negative impacts of cropping management on soil structure and water-holding capacity (Larkin 2015). This may include reducing cultivation depth and intensity (Reid & Morton 2019). Minimising the time the land is in fallow, and particularly avoiding winter fallow periods, can help to reduce nutrient losses and soil erosion (Reid & Morton 2019).

5 Conclusions

The use of soil conditioners, including biochar, compost, straw, sawdust, crop residues, and green manure, has been shown to reduce nitrate leaching from soils and to have additional benefits, including increasing soil organic matter and structure. However, the use of these amendments to mitigate nitrate leaching from Ranzau soils under intensive vegetable production needs to take into account the site-specific soil properties that may limit the efficacy of these amendments. These include the coarse texture, shallow depth, and free-draining nature of these soils.

Given these properties, even with the use of soil amendments, Ranzau soils present reduced opportunity for attenuation of nitrate and provide rapid transport to groundwater. Therefore, careful evaluation focus should be given to reducing the sources of excess nitrogen to these soils, even with the use of mitigations such as soil amendments. Excess irrigation should also be avoided. Finally, the suitability of intensive land use on these soils should be considered.

6 Recommendations

Given the shallow depth of Ranzau soils, it is critical to develop a thorough understanding of nitrogen cycling in these cropping systems, and the relationship of this cycling to management practices (including irrigation and fertiliser applications for the specific crops being grown) in order to better quantify the potential benefits of soil amendments to minimise nitrate leaching.

7 Acknowledgements

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