



## REVIEW ARTICLE

# The effects of pastoral hill country natural landscape features and land management practices on nitrate losses and its potential attenuation for improved water quality

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### Abstract

Pastoral farming on hill country landscapes influences nitrogen (N) dynamics and its losses to freshwater. This study reviewed the current literature identifying key effects of pastoral hill country landscape features and land management practices on nitrate losses to receiving waters. The review also highlighted the potential effects of inherent landscape features on nitrate attenuation pathways for better water quality outcomes. Intensive land use activities involving high rates of fertiliser application, higher stocking rates and cattle grazing, relative to sheep grazing, are more likely to increase nitrate loss, especially on lower slopes. However, soils with a high carbon (C) storage capacity such as allophanic soils potentially limit nitrate loss via denitrification in subsoil layers. Hill country seepage wetlands also offer an opportunity to attenuate nitrate loss, though their efficacy is largely impacted by hydrological variations in their inflows and outflows. By enhancing the natural nitrate attenuation capacity of seepage wetlands, mapping and strategic use of high subsoil denitrification potential, effective riparian management, efficient fertiliser and grazing practices and the incorporation of these farm management strategies into Freshwater Farm Plans (FWFPs), wider environmental and farm productivity/profitability goals, including improved water quality, would be achieved on pastoral hill country landscapes.

### KEYWORDS

Freshwater Farm Plans, New Zealand, seepage wetlands, soil types, topography

## 1 | INTRODUCTION

Hill country landscapes are low-altitude lands (<1000 m above sea level) with predominately rolling and steep slopes (>15°). They occupy approximately 4 million ha of New Zealand (NZ) land mass (Beef+Lamb NZ, 2020), and support sheep, beef cattle and deer farming. Compared with dairy farms, pastoral hill country farms in NZ are generally not as intensively managed in terms of stocking rate and fertiliser use. This is consistent with the low-intensity grassland

management systems in Europe (Caballero et al., 2007). Despite its low-intensity management, pastoral hill country farming is increasingly being identified as a diffuse source of nutrient [nitrogen (N) and phosphorus (P)] losses to receiving freshwaters (Hoogendoorn et al., 2017; McDowell, 2006; Quinn et al., 1997). Nitrate losses from NZ pastoral hill country range from 1 to 44 kg NO<sub>3</sub>-N ha<sup>-1</sup> y<sup>-1</sup> (Dodd et al., 2016), with variations influenced by soil/rock types and farm management practices. Catchment-scale modelling suggests that ~77% of NZ's nitrate-N load is generated from low-order

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streams which are common in hill country landscapes (McDowell et al., 2017). Nutrient losses contribute to water quality degradation which is a major national and global environmental issue that has several negative consequences, including the impairment of drinking water quality, excessive algal growth and loss of biodiversity in receiving freshwaters (Camargo et al., 2005; Davies-Colley, 2013; Davis & Koop, 2006; McLarin et al., 1999). Recently, NZ introduced the Essential Freshwater package (Ministry for the Environment and Ministry for Primary Industries, 2020) which focuses on improving freshwater quality within 5 years through a series of targeted regulations, including compulsory farm-specific Freshwater Farm Plans (FWFPs) to identify and mitigate nutrient losses from farms to receiving waters. It is necessary to develop farming practices that limit nutrient losses from pastoral hill country farms while maintaining/improving farm productivity and profitability. Therefore, sound knowledge and tools to map and manage critical source areas (CSAs) and critical flow pathways of nutrient losses from pastoral lands are of key importance for the implementation of environmentally sensitive land management practices.

Leaching and subsurface flow are the major pathways for N losses from agricultural lands to receiving waters. However, a range of landscape features and biogeochemical processes influence N fluxes and its potential attenuation in critical flow pathways (Collins et al., 2017; Elwan et al., 2018; Rivas et al., 2020). Subsurface denitrification (denitrification below the root zone) has been identified as an important nitrate attenuation process that limits N losses in subsurface flow pathways (Rivett et al., 2008). Under favourable hydrogeological conditions, complete denitrification seems more prevalent in subsurface environments such as subsoil layers, seepage wetlands and ground waters due to the limited oxygen supply in these environments (Jha et al., 2018; Peterson et al., 2013; Uuemaa et al., 2018). Hence, the accumulation of nitrous oxide—a potent greenhouse gas (GHG) (IPCC, 2014; Ravishankara et al., 2009)—is typically restricted under complete denitrification in favourable subsurface conditions (Jha et al., 2018). Moreover, the limited gas exchange between the subsurface soil layers and the atmosphere restricts the transport of any produced nitrous oxide from the soil to the atmosphere (Stenger et al., 2013). This contrasts with what is prevalent in the surface soil, where higher oxygen availability and substrate supply (especially on pasture soils) encourage incomplete denitrification and nitrous oxide emissions (Dangal et al., 2019).

The efficiency of subsurface denitrification is influenced by soil moisture content and drainage characteristics, underlying hydrogeology, and supply/availability of dissolved organic carbon (DOC) (Barkle et al., 2007; Chibuike et al., 2021; Clague et al., 2013; Jha et al., 2018; Peterson et al., 2013; Rivas et al., 2020; Starr & Gillham, 1993). Several studies have been conducted to measure nitrate losses and its potential attenuation via denitrification in pastoral hill country landscapes (Burkitt et al., 2016; Burns & Nguyen, 2002; Chibuike, Burkitt, Bretherton, et al., 2019; Chibuike et al., 2020; Matheson et al., 2002; Rutherford & Nguyen, 2004; Sanwar, 2023). The unique features of pastoral hill country landscape

(e.g., topography and soil characteristics) have the potential to influence the efficiency of subsurface denitrification by affecting the availability of substrates, particularly DOC, required for denitrification below the soil surface (Chibuike, Burkitt, Bretherton, et al., 2019; Sanwar, 2023). A sound understanding of how pastoral hill country landscape features influence nitrate losses to receiving waters is imperative in tackling the issue of water quality degradation. Furthermore, an assessment of the potential impacts of relevant pastoral hill country landscape features and management practices on nitrate fluxes would enable catchment scale assessment and implementation of targeted and effective measures to enhance nitrate attenuation capacity in pastoral hill country landscapes.

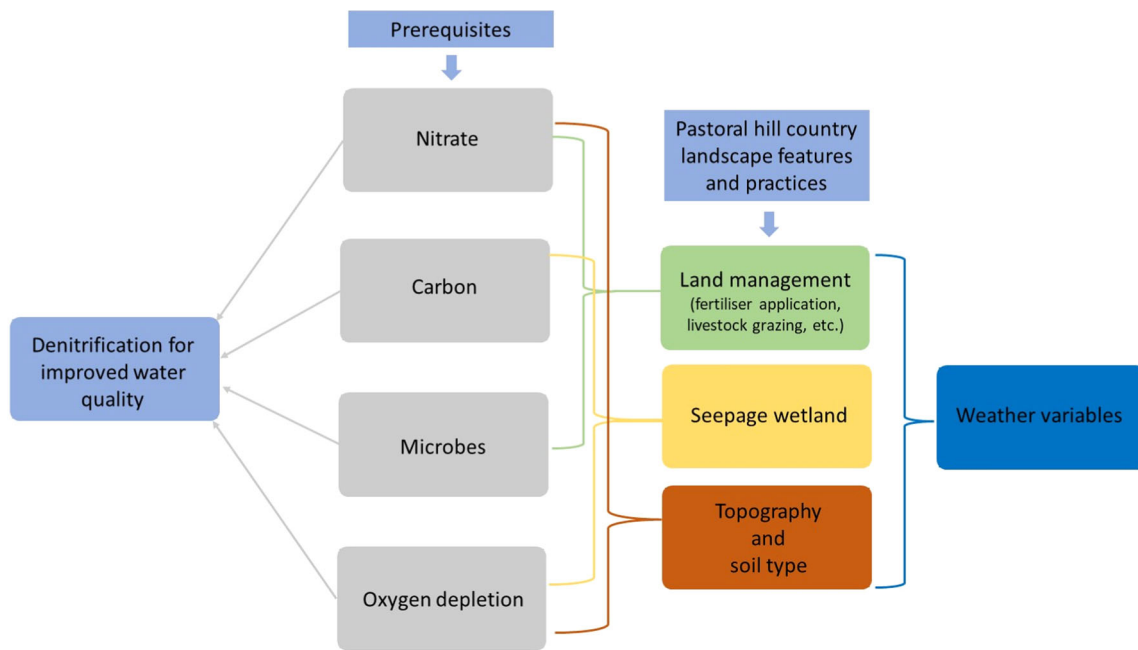
This paper aimed to (i) discuss the contributions of relevant pastoral hill country landscape features and farming practices to nitrate loss and their potential impact on subsurface denitrification for improved water quality outcomes and (ii) recommend farm management strategies to achieve effective mitigation of nitrate loss from NZ pastoral hill country landscapes. The findings of this review are expected to benefit effective nutrient management not only in NZ pastoral hill country landscapes but also in similar grazed hill country catchments in other countries such as Ireland, Scotland and Chile.

## 2 | EFFECTS OF LANDSCAPE FEATURES AND LAND MANAGEMENT PRACTICES ON NITRATE LOSS AND ITS POTENTIAL ATTENUATION

The unique features of pastoral hill country landscapes, and land management practices within these landscapes, influence nitrate attenuation through their effect on the prerequisites for denitrification (Figure 1). The impact of landscape features/practices on nitrate losses and its potential attenuation is largely influenced by weather variables such as rainfall. In the following subsections, we review and discuss how NZ pastoral hill country landscape features and management practices influence nitrate fluxes and its potential attenuation for better water quality outcomes. We also refer to relevant studies from other countries practising pastoral hill farming.

### 2.1 | Land management practices

Pastoral hill country farmers use fertiliser nutrients [P, potassium (K) and sulphur (S)] and pH ameliorant lime to boost pasture production and quality (Roberts & White, 2016). Nitrogen fertiliser is sometimes applied to improve pasture growth on selected paddocks or across the farm (Beef+Lamb NZ, 2023). Nitrate leaching from applied N fertilisers in pastoral hill country depends on several factors, including fertiliser application rate, timing, weather, slope and soil properties. However, linear increases in N leaching with increased N fertiliser application rates have been reported across NZ hill country farms (Crofoot et al., 2010; Hoogendoorn et al., 2017; Morton &



**FIGURE 1** Nitrate attenuation as influenced by pastoral hill country landscape features and management practices. Pastoral hill country landscape features and practices control the availability of the prerequisites for denitrification, and weather variables influence their impact on nitrate loss and potential attenuation for improved water quality.

Stevens, 2023). Hoogendoorn et al. (2017) estimated an increase of 11%–29% in nitrate leaching at a fertiliser application rate of 20–50 kg N ha<sup>-1</sup>, which are rates commonly applied across NZ hill country farms. Research by Scott et al. (2015) on the Ballantrae Hill Country Research Farm near Woodville in NZ showed that combining both P and N fertilisers can potentially limit nitrate leaching due to greater pasture N uptake in the presence of P fertilisers. The authors also found greater DOC leaching under N and P fertiliser input which is associated with greater solubilisation of organic matter due to soil pH increases following fertiliser application. However, several factors, including grazing management, potentially influence DOC leaching under such fertiliser combinations (Parfitt et al., 2009; Scott et al., 2015). Research on Ballantrae and another hill country farm at Invermay, NZ (Letica et al., 2006) indicated that lower slope areas (camp sites) and soils with high pH (>6) have greater nitrification potential and a higher tendency for nitrate loss following N fertiliser application. This highlights the interaction between landscape features and land management practices that influence potential nitrate leaching loss from the soil profile. These findings support the use of targeted fertiliser applications, guided by a robust soil testing and consideration of landscape features, to reduce nitrate losses from pastoral hill country soils.

Relative to cattle grazing, sheep grazing results in lower surface runoff and nutrient losses from hill country landscapes (Bunyaga et al., 2023; Lambert et al., 1985). Grazing cattle generally causes greater treading damage and soil compaction (Nguyen et al., 1998). Hoogendoorn, Betteridge, et al. (2011) recorded greater leaching losses of mineral-N (ammonium-N and nitrate-N) from cattle-grazed areas compared with sheep- and deer-grazed areas in an intensively

grazed pasture in Lake Taupō. These differences in N leaching losses are less likely to be due to variations in livestock urine N concentrations since Hoogendoorn et al. (2010) observed inconsistent differences in the urine N concentration of cattle, sheep and deer grazing a common pasture, though urine volume and urination frequency were not assessed in their study. Cattle generally produces larger urine volumes resulting in large N loading in cattle urine patch, which is prone to leaching especially during autumn (Selbie et al., 2015). The greater moisture content and dispersibility of cattle dung, compared with sheep and deer dung, have been shown to stimulate greater nutrient losses from cattle dung in overland flow (McDowell, 2006). Moreover, cattle dung contains greater N content and has been shown to increase soil nitrate concentration, and microbial biomass and activity relative to sheep and deer dung (Williams & Haynes, 1995). Limiting livestock grazing during periods of high rainfall (e.g., winter months) has also been shown to reduce nitrate leaching from pastoral hill country (Betteridge et al., 2007). Interestingly, Hoogendoorn et al. (2016) observed that increasing grazing intensity/stocking rate (annual average standing biomass: 1475 vs. 1900 kg DM ha<sup>-1</sup>), across a range of slope classes (<13 to >25°), did not influence leaching losses of nitrate and DOC in the short-term (3 years) at Ballantrae. Their finding supports a previous modelling study (Hoogendoorn, Bowatte, et al., 2011) which reported that grazing intensification would only result in C and N losses if the amount of herbage removed was three times greater than the net herbage accumulation.

The replacement of perennial pasture with winter forage crops has been adopted on many NZ hill country farms to increase animal feed production during periods of lower pasture growth (winter



months) (Burkitt et al., 2017; Houlbrooke et al., 2009). Historically, crop establishment on steeper land was carried out using the aerial spraying and surface seeding technique (spray and pray) due to the difficulty of using machinery on sloping landscapes (Burkitt et al., 2017; Chibuike et al., 2021). Whereas Intensive Winter Grazing regulations under the National Environmental Standards (part of the Essential Freshwater package of regulations) released in 2020 now only permit forage crop grazing on land that is 10° or less in slope (Beef+Lamb NZ, 2022). There is evidence intensive winter cropping practice increases surface runoff and N losses (Monaghan et al., 2017), especially from imperfectly drained soils (Burkitt et al., 2017). The establishment of winter forage crop using the 'spray and pray' technique also has the potential to cause an initial increase in the DOC and nitrate concentrations of the surface 0.2 m soil depth (without livestock grazing), because of the effects of the agrochemicals used in clearing out pasture as well as N mineralisation in the surface soil (Chibuike, Burkitt, Camps-Arbestain, et al., 2019; Chibuike et al., 2021). However, the transport of DOC generated from forage cropping through the soil layers, and thus its potential effect on subsurface denitrification, varies with soil type (drainage class) and climatic variables (rainfall). The fast turnover of exogenous DOC is also likely to limit the transport of the generated DOC through the soil profile (Chibuike, Burkitt, Camps-Arbestain, et al., 2019; Hagedorn et al., 2012). Other research on hill country forage cropping (Betteridge et al., 2007) showed that relative to annual forage cropping, perennial forage cropping, which requires lower fertiliser application and ensures permanent plant cover, reduced nitrate leaching (to the 60 cm depth) at the Waituhi Kuratau hill country farm.

Non-grazed native vegetation occupies 15% of NZ hill country farmland area while plantation forestry occupies 3% (Beef+Lamb NZ, 2020). Forested catchments typically have a higher capacity to reduce surface runoff and hence nutrient losses compared with paired hill country catchments (Bargh, 1977, 1978; Quinn & Stroud, 2002). Quinn and Stroud (2002) reported higher nitrate-N in a stream draining an intensively stocked pasture (13 stock units ha<sup>-1</sup>) compared with a nearby native forest at the Whatawhata Hill Country Research Centre. Silvopasture, integrating targeted forestry in pastoral hill country, could potentially affect pastoral production and its associated nutrient losses in pastoral catchments. However, the impact of trees on nutrient dynamics in pastoral hill country depend on several factors such as fertiliser history, animal access to the tree sites, and tree age (Davis, 2001). Research by Mackay-Smith et al. (2022) on a kanuka tree pasture in the Wairarapa region is the only hill country study to date that has assessed the effect of silvopasture on surface runoff and nutrient losses in NZ pastoral hill country. The authors found greater surface runoff and nitrate losses under trees, relative to open pasture, because the pasture under trees was preferentially grazed by livestock which resulted in lower grass cover/physical barrier and hence greater soil and nutrient losses.

Riparian buffers with trees and/or fences are common within pastoral hill country farms. These buffers decrease the transport of contaminants (including faecal coliforms, sediments, P and N) from

farms to surrounding surface waters by limiting animal access to streambanks (Dodd et al., 2016). However, catchment scale nitrate attenuation via riparian management is likely to be influenced by groundwater flow pathways and residence time. Stream nitrate levels may continue to increase for a while in catchments with high nitrate reserve in groundwater even after buffer establishment (Dodd, Quinn, et al., 2008; Williamson et al., 1996). In addition, the shedding of herbaceous trees used for riparian management is likely to stimulate sediment and nutrient losses from streambanks supporting newly established trees during the establishment phase (Collier et al., 2001) because it generally takes more than 5 years for trees to develop sufficient root biomass to limit soil and nutrient losses (Hicks et al., 1993). Furthermore, the intensive weed management typically required during riparian establishment (McKergow et al., 2016; Parkyn, 2004) could present a significant barrier to adopting riparian buffers.

## 2.2 | Topography

Hill country topography significantly influences the spatial distribution of soil moisture and substrates for subsurface denitrification. Grazing animals tend to graze and rest (camp) on lower slopes than on steeper slopes. This results in the nonhomogeneous distribution of urine and dung along the catena, with a reduction in nutrient accumulation as slope increases (Letica et al., 2006; Saggari et al., 1999). The accumulation of nutrients, runoff and seepage water on flat (low) slopes makes them CSAs with greater potential for nitrate leaching, due to their accumulation and rapid transport processes. For instance, Crofoot et al. (2010) found higher nitrate-N leaching at low (0–12°) and medium (13–25°) slopes compared with high (>25°) slope in a hill country farm in the Wairarapa region of NZ. Similarly, consistent with the higher soil nitrification potential observed at low slopes (Devantier et al., 2012; Letica et al., 2006), Hoogendoorn et al. (2016) reported greater nitrate-N leaching on low (68 kg ha<sup>-1</sup>) versus medium (5 kg ha<sup>-1</sup>) slopes at Ballantrae Research Farm in NZ. The authors, however, did not observe differences in the amount of DOC leached from these slope classes. On an 'average' pastoral hill country farm, low, medium and high slopes occupy 30%, 40% and 30%, respectively, of the total grazing area (Saggari et al., 1990). Therefore, nitrate losses are likely to be substantial from low to medium slopes, making them CSAs in pastoral hill country landscapes; effective management practices are, thus, required to limit N losses from these CSAs.

To date, there are limited studies on the potential effects of slope and soil type on the transport and transformation of nitrate at depth in the soil profile on pastoral hill country landscapes. In a study assessing potential denitrification activity at the Tuapaka hill country farm near Palmerston North in NZ, Chibuike, Burkitt, Bretherton, et al. (2019) found more than 50% lower denitrification capacity below the 0.3 m soil depth compared with the surface 0.3 m soil depth, but soil type rather than slope had a greater effect on denitrification capacity (see Subsection 2.3 for additional information on this soil type). In general, slope affects seepage water flows, with longer groundwater residence time and hence potentially higher denitrification potential on toe slopes



(Messer et al., 2012; Ocampo et al., 2006). This convergence and slow movement of subsurface water flows in toe slope/gullies and valleys modifies soil moisture conditions and creates an environment suitable for denitrification to occur in the soil profile (see Subsection 2.4 for information on seepage wetlands).

Aspect potentially influences N transport and transformation in pastoral hill country landscapes. Compared with northern aspects, southern aspects tend to retain more soil moisture and thus supports clover growth, which when grazed by livestock supplies N to the soil (Beef+Lamb NZ, 2023). Lambert and Roberts (1978) reported greater N mineralisation on eastern aspect relative to southern, northern and western aspects at Ballantrae Research Farm. This was largely influenced by animal camping behaviour as they avoided the areas with greater wind speed. To date, the contribution of aspect to subsurface denitrification on NZ pastoral hill country landscape is yet to be explored. It is likely that aspects which retain soil moisture and/or encourage animal camping behaviour will potentially have higher denitrification capacity but how topography (slope and aspect) influence nitrate attenuation below the soil surface warrants further investigation to aid in the adoption of effective management practices that limit nitrate loss from pastoral hill country.

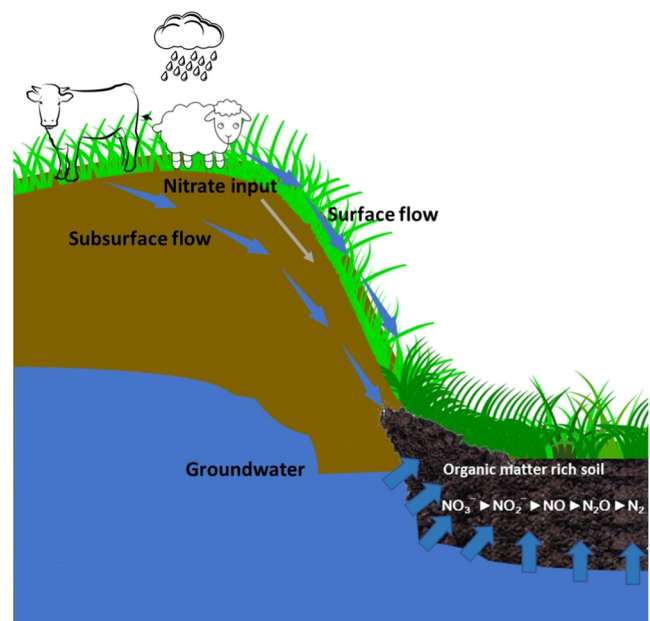
### 2.3 | Soil type

Soil development in hill country is primarily influenced by topography, with deeper and more fertile soils found at the bottom of slopes, and shallower, less fertile and, in most cases, well-drained soils found on steeper areas that are prone to erosion (Molloy, 1998). When varying soil drainage classes occur on similar slope, imperfectly/poorly drained soils are generally more prone to higher nutrient losses via runoff than well-drained soils because of slower infiltration and less drainage on the poorly drained soils. For instance, research on Tuapaka hill country farm in NZ (Burkitt et al., 2017; Fransen et al., 2023) showed greater surface runoff and total N losses from a catchment with an imperfectly drained soil relative to a catchment with a well-drained soil even though both catchments had similar slope and size. In each of the Tuapaka studies (Burkitt et al., 2017; Fransen et al., 2023), the effect of a specific land management practice on surface runoff was assessed, that is, cattle supplement feeding (Fransen et al., 2023) and forage cropping (Burkitt et al., 2017). However, while both studies reported lower losses of sediments, and total P and N in surface runoff from the well-drained soil, Burkitt et al. (2017) observed slightly higher nitrate in surface runoff from the well-drained soil. This is interesting as surface runoff is not a major pathway for nitrate loss and well-drained soils are typically more prone to nitrate loss via leaching. Although these observations were from short-term studies ( $\leq 1$  year), they suggest that contrasting land management practices could differentially affect surface soil properties and the potential for nitrate loss via surface runoff. However, longer-term monitoring is required to better understand this interaction especially under different climatic seasons. It is worth noting that Chibuike, Burkitt, Bretherton, et al. (2019) observed higher denitrification capacity below the surface 0.3 m soil

depth of Ramiha (a well-drained soil) compared with other soil types on Tuapaka hill country farm. They attributed the high denitrification capacity to the soil's greater DOC concentration ( $>100 \text{ mg kg}^{-1}$  below 0.3 m depth) resulting from its high content of short-range order constituents (allophane). Therefore, carrying out more intensive farming practices such as winter cropping or cattle feeding on well-drained soils with high potential for subsurface denitrification (e.g., Ramiha soil) would likely limit nutrient losses to receiving waters. Appropriate farm delineation would help identify such soils and aid in the adequate management of pastoral hill country farms. This approach has been shown to be effective for the management/restoration of degraded hilly agricultural landscapes in Chile (Lebuy et al., 2023).

### 2.4 | Seepage wetland

Naturally wet areas such as seepage wetlands and hillside seeps are common features of hill country landscapes. The presence of these wet areas in hill country is primarily linked to the varied topography in these landscapes, which result in areas with contrasting soil moisture contents. Hillside seeps are usually less than  $10 \text{ m}^2$  wet areas on hillsides where groundwater discharges at the soil surface, whereas seepage wetlands are generally larger ( $10\text{--}5000 \text{ m}^2$ ) boggy areas in valleys (Chibuike et al., 2020). Seepage wetlands are comprised of unconsolidated soils and are predominately wet due to their proximity to streams. They are fed mainly by subsurface flow from springs or by seepage from the ground (Rutherford et al., 2018), but can also possess a surface flow dominated hydrology (Sanwar, 2023). Seepage wetland soils are typically rich in organic matter (Figure 2),



**FIGURE 2** Pastoral hill country seepage wetland showing the conditions that support denitrification—water input (oxygen limitation), nitrate input and an organic matter rich soil.



probably due to slower organic matter decomposition in the oxygen-limited environment. Pastoral seepage wetlands are often referred to as 'kidneys of the landscape' because of their ability to capture and transform farm nutrients before they reach water bodies (Rutherford et al., 2018).

Seepage wetlands have been found to reduce nitrate losses to receiving waters across NZ pastoral hill country landscapes (Burkitt et al., 2015; Cooper, 1990; Matheson et al., 2002; Rutherford et al., 2009; Sanwar, 2023). Rutherford et al. (2009) observed that seepage wetlands occupying 5% of a hill country catchment near Lake Taupō could potentially attenuate nitrate in 11%–19% of runoff. Seepage wetlands are able to remove 75%–98% of nitrate from water mainly through denitrification and plant uptake (Cooper & Cooke, 1984; Rutherford et al., 2018). Plant nitrate uptake is not a permanent nitrate attenuation pathway as N is returned to the soil when the plants die. However, harvesting seepage wetland plants could permanently remove nitrate from the wetland system (Mander et al., 1995). Furthermore, Matheson et al. (2002) reported that seepage wetland plants promoted denitrification (over dissimilatory nitrate reduction to ammonium) through rhizosphere oxidation of anoxic soils at the Whatawhata Hill Country Research Centre.

At the Tuapaka hill country farm in NZ, Chibuikie et al. (2020) observed that hill country seepage wetlands had four times more DOC in the surface 0.3 m soil depth relative to the surrounding dry area soil. The authors also noted that the DOC of the seepage wetland was readily available (had lower molecular weight) to support denitrification in the soil-water system, hence the observed higher denitrification capacity of the seepage wetland relative to the surrounding dry area soil. In a multisite seepage wetland study involving four pastoral hill country farms in the Manawātū region of NZ, Sanwar (2023) observed that other soil/sediment properties such as moisture content, nitrate, total C and N, C:N, dissolved iron ( $\text{Fe}^{2+}$ ) and manganese ( $\text{Mn}^{2+}$ ) concentrations also positively influence denitrification potential in seepage wetlands. It is worth noting that C decomposition in oxygen-limited conditions prevalent in wetlands make them a potential source of methane emissions (Bridgman et al., 2013). However, pastoral seepage wetlands are usually small (Uuemaa et al., 2018), and compared to the ecosystem role they play in improving water quality and providing habitat for native flora and fauna, methane emission from pastoral seepage wetlands is considered negligible (Wilcock et al., 2008), though this requires further investigation.

Several factors affect the capacity of seepage wetlands to attenuate nitrate losses, including hydrological flow characteristics, vegetation, soil type, amount of nutrient input and climatic conditions (Abbasi et al., 2019; International Water Association, 2000; Rutherford et al., 2018). With more water moving across the top of seepage wetlands than through the soil profile, the decrease in soil porosity with depth reduces vertical mixing of water and thus limits the transport of nitrate to denitrifying microbes. This lack of vertical mixing could potentially limit denitrification capacity with depth in seepage wetlands even when substrates are present deeper in the soil profile (Rutherford & Nguyen, 2004; Rutherford et al., 2018).

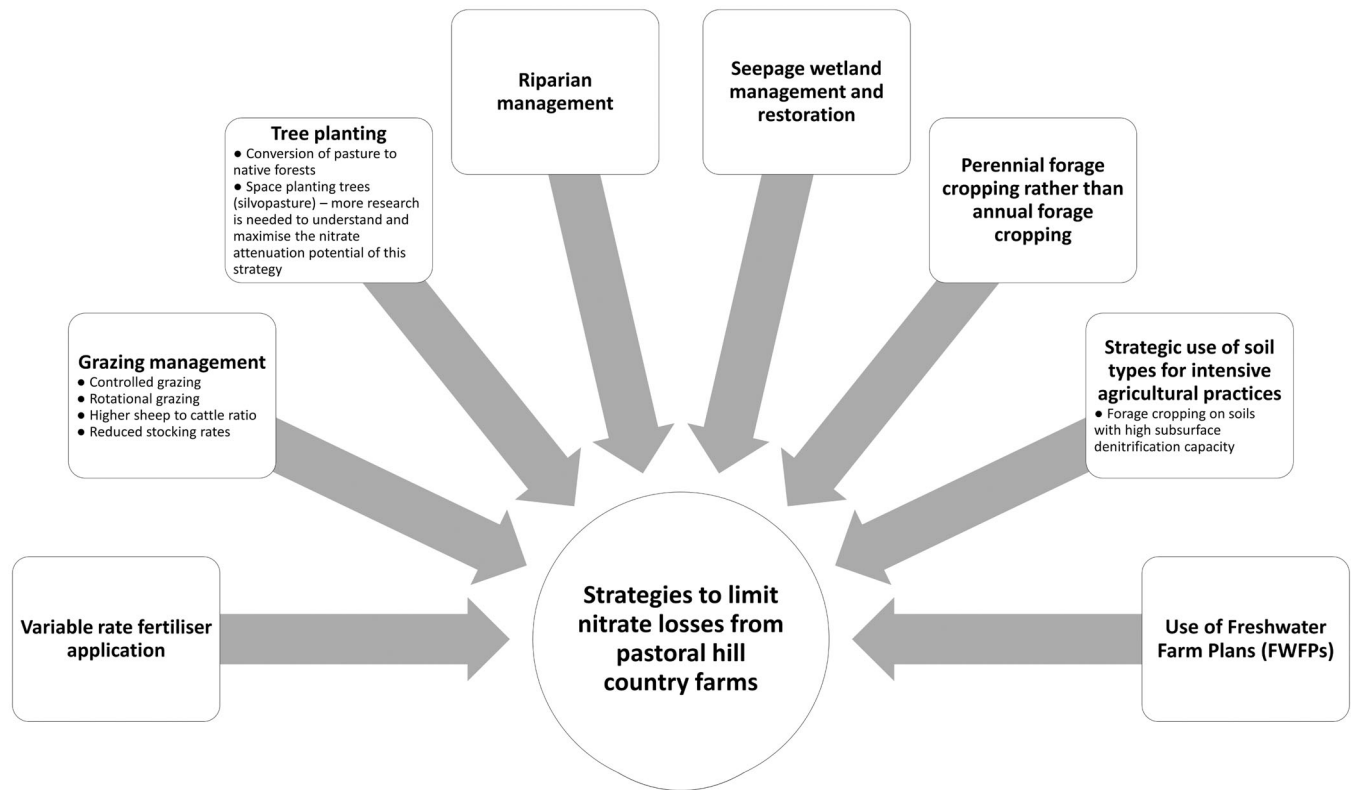
Seepage wetlands can be sources of nitrate (as well as ammonium, organic and particulate N) during periods of high rainfall intensity (Rutherford et al., 2017; Sanwar, 2023; Zaman et al., 2008). This is because high flows (during intense rainfall events) reduce the contact time between water and soil and thus decreases the nitrate attenuation capacity of seepage wetlands, while the reverse is the case with low flows. However, animal grazing was found to potentially make seepage wetlands sources of nitrate during periods of low flows (Sanwar, 2023). Grazing animals compact the soil and create channels in wetlands; thus, they reduce vertical mixing and water residence time which decreases subsurface denitrification in seepage wetlands (Rutherford et al., 2017). Given the potential of pastoral hill country seepage wetlands to limit nitrate loss to receiving waters, strategies that maintain/enhance their nitrate attenuation capacity is therefore necessary (see more details in Section 3).

### 3 | EFFECTIVE FARM MANAGEMENT STRATEGIES TO REDUCE NITRATE LOSSES FROM PASTORAL HILL COUNTRY LANDSCAPES

Nitrate losses from pastoral hill country farms can be mitigated by adopting the farm management strategies summarised in Figure 3. In this section, we review and discuss the effectiveness of these management strategies in reducing nitrate losses from pastoral hill country farms.

Over 50% of NZ pastoral hill country studies related to soil N dynamics have focused on the effects of land management practices (Table A1). Given that land management significantly influences nitrate losses to freshwaters, it is important that adequate and sustainable practices are adopted to limit nitrate losses from hill country farms. One such practice is precision fertiliser application, which is supported by the body of literature on the impact of fertiliser application on nitrate losses (Crofoot et al., 2010; Hoogendoorn et al., 2017; Morton & Stevens, 2023). Variable rate fertiliser strategies help achieve precision fertiliser application by first identifying the production potential of hill country Land Units (LUs), assessing the soil characteristics/fertility of the LUs (via soil and herbage sampling), and then applying the appropriate fertiliser rates to obtain an economic optimum soil fertility based on the identified production potential (White et al., 2017). Thus, this strategy helps achieve both economic and environmental goals because non-productive areas and/or environmentally sensitive areas are avoided during fertiliser application (Morton et al., 2016), limiting any accidental direct fertiliser application (via aerial spreading) to nontarget areas such as waterways.

Pastoral hill country farms receive an average of  $12 \text{ kg N ha}^{-1}$  on pasture, with most of the fertiliser applied to the feed crop area ( $63.4 \text{ kg N ha}^{-1}$  crop) which make up 2.9% of the whole farm area (Beef+Lamb NZ, 2020). Fertiliser N application is typically done during late winter/early spring, that is, when livestock (lactating ewes



**FIGURE 3** Management strategies to limit nitrate losses from pastoral hill country farms.

and cows) feed requirements are high but pasture production is limited by low soil temperatures. Beef+Lamb NZ (2023) recommends applying 30–50 kg N ha<sup>-1</sup> at one time on the northerly aspects (sunny and steep slope for better pasture response) 4–6 weeks before lambing or calving for maximum results during late winter/early spring. At least 20–30 mm of rainfall is required to initiate pasture growth if N is to be applied during autumn to boost winter feed production. Technologies that map soil/plant nutrient status and soil moisture (Dehghan-Shoar et al., 2023; Hajdu et al., 2019), combined with weather forecasting tools could facilitate precision fertiliser application on pastoral hill country landscapes. It is worth reiterating that forage cropping practices that ensure permanent land cover with minimal fertiliser input (e.g., perennial rather than annual forage cropping) also significantly reduce nitrate loss from hill country landscapes (Table 1). Carrying out intensive farming practices (that require fertiliser application) on well-drained soils with high subsurface denitrification capacity will also limit nitrate loss to freshwater.

Restricted grazing during periods of high nutrient loss (winter months) can potentially reduce nitrate leaching loss by 64% (Table 1). Rotational grazing to fully utilize grown pasture at all times of the year help reduce surface runoff and associated nutrient losses, including nitrate (Lambert et al., 1985). Other grazing management options that alter stock ratio or numbers for improved environmental outcomes, for example, reducing stocking rates and increasing sheep-to-cattle ratio, potentially limit nitrate loss but they also directly

influence the farm business profitability and thus are unlikely to be easily adopted (Dodd et al., 2016). Moreover, protecting CSAs via controlled grazing of winter forage crops could potentially limit N and other contaminant losses in surface runoff (Ghimire et al., 2023).

Strategically planting trees (both native and exotic) within pastoral hill country provide multiple benefits such as erosion control, better water quality, indigenous species conservation, GHG mitigation, and economic sustainability of the farms, including timber and/or honey production (Dodd et al., 2008b). As discussed in Subsection 2.1, the effectiveness of trees (and shrubs) in improving water quality is influenced by several factors, including animal access to the trees. The conversion of existing pastoral areas to native forests, without animal access, has a high potential to limit nitrate loss from hill country landscapes (Table 1) while also maintaining the landscape's biodiversity (Quinn & Stroud, 2002). However, the common practice of space planting trees across erosion-prone sites in pastoral hill country farms (silvopasture) could potentially increase runoff and nutrient losses due to animal preferential grazing under trees (Mackay-Smith et al., 2022). Thus, further research is needed to better understand how such losses vary with respect to different tree configurations, soil types and topography within pastoral hill country landscapes. Future studies of this nature would provide more information if they included long-term monitoring of how tree age and the number and distribution of trees within a grazed pasture paddock influence nitrate loss to both surface- and groundwater. Moreover, the cumulative effects of silvopasture practices on runoff

**TABLE 1** Effectiveness of relevant farm management strategies to limit nitrate losses from NZ pastoral hill country.

Management strategy	Effectiveness in nitrate loss reduction (%)	Pathway	References
Reduction in fertiliser application rate	80 <sup>a</sup>	Leaching	Hoogendoorn et al. (2017)
<i>Grazing management</i>			
✓ No grazing during winter	64	Leaching	Betteridge et al. (2007)
✓ Cut and carry	86	Leaching	Betteridge et al. (2007)
✓ Stocking with sheep (relative to cattle)	30	Leaching	Hoogendoorn, Betteridge, et al. (2011)
✓ Rotational grazing	10 <sup>b</sup>	Surface runoff	Lambert et al. (1985)
Perennial forage cropping (relative to annual forage cropping)	90	Leaching	Betteridge et al. (2007)
Conversion to native forest	92	Runoff	Quinn and Stroud (2002)
Silvopasture	-277 <sup>c</sup>	Surface runoff	Mackay-Smith et al. (2022)
Riparian management	-26 <sup>d</sup>	Runoff	Williamson et al. (1996)
Wetland management	<1 to 41 <sup>e</sup>	Surface and subsurface	Sanwar (2023)
	24	Surface	Rutherford and Nguyen (2004)
	92	Subsurface	Burns and Nguyen (2002)

<sup>a</sup>Mean effectiveness of lowest fertiliser rate (100 kg N ha<sup>-1</sup> year<sup>-1</sup>) relative to highest rate (750 kg N ha<sup>-1</sup> year<sup>-1</sup>).

<sup>b</sup>Calculated from the proportion of mineral-N in total N.

<sup>c</sup>Calculated from mean nitrate-N concentrations; the effectiveness of silvopasture was influenced by animal preferential grazing under trees.

<sup>d</sup>Effectiveness was influenced by inputs of nitrate from groundwater.

<sup>e</sup><1% during high flow (Year 1) and 41% during low flow (Year 2).

and nutrient losses at farm- and catchment-scale require further investigation.

Riparian management with tree and/or fences helps limit livestock access (and hence nutrient input) to surface waters. Using herbaceous species for riparian management can be effective for trapping sediment and nutrient losses; however, if the herbage is not harvested, their nutrient storage capacity can be exceeded (Dodd et al., 2016). Controlled grazing of these riparian areas can be used as a management strategy to 'harvest' the nutrient-rich plants (Taranaki Regional Council, 2023). Although controlled grazing of hill country wet areas potentially increases nitrate losses to receiving waters, Black et al. (2015) noted that impairment of surface water quality via this approach can be short-lived, with stream nutrient concentrations returning to background levels 2 h after livestock grazing. However, caution should be exercised when applying this finding as effects would vary depending on livestock type (sheep vs cattle), grazing duration, soil characteristics and proximity to receiving waters.

Seepage wetland management/restoration is a cost-effective strategy (Dodd et al., 2016) for limiting nitrate losses from pastoral hill country landscapes, especially during periods of low flow. Farmers usually drain seepage wetlands to prevent animals getting mired (Tanner et al., 2015). However, both NZ and international studies have shown that draining pastoral wetlands impacts on biodiversity (Clarkson et al., 2013; Stratigos, 2022). Fencing seepage wetlands (rather than draining them) to ensure controlled grazing would help limit animal treading damage (and its associated nutrient losses) and so maximise the

nitrate attenuation capacity of these unique hill country landscape features. Selecting the right plants for wetland restoration is also important because compared with smaller plants, larger plants such as trees and shrubs create flow channels which reduce water residence time, although these large plants could potentially prevent erosion during heavy storms (Rutherford et al., 2018). It is worth noting that research on hill country seepage wetlands have focused on understanding how their soil/sediment and hydrological characteristics affect nitrate removal. However, more research is needed to understand how variations in hydrology (rainfall amount and distribution) influence the attenuation capacity of these wetlands and also how attenuation could be optimised by controlling water flow and increasing residence time, for example, via vertical downwelling of pastoral surface runoff into seepage wetlands to maximise their subsurface nitrate attenuation capacity (Sanwar, 2023). In addition, there are limited studies on how the soil microbial community (associated with N transformation processes within these wetlands) changes in response to different land management practices, wetland plants, and climatic/weather variables. Measurements of soil microbial abundance, composition, and/or activity within seepage wetlands and across the different hill country landscape features and practices would also inform modelling studies and help in the sustainable management of NZ pastoral hill country farms.

Adopting any management strategy to limit nitrate losses from pastoral hill country farms requires consideration of its suitability, effectiveness (which is influenced by several factors as highlighted in Section 2) and the cost of making such changes on the farms'



productivity and profitability (Dodd et al., 2008a, 2016). Historically, NZ farms have used Soil Conservation plans and then more recently Farm Environment Plans (FEPs) and FWFPs to manage soil erosion and broader environmental impacts, respectively (Burkitt & Bretherton, 2022; Stokes et al., 2021). In 2023, Resource Management (FWFP) regulation became law, meaning that every NZ farm more than 20 ha in size and all horticultural land use greater than 5 ha in size require a certified FWFP by 2025. A FWFP identifies inherent risks associated with the farms natural resources and management to identify a set of actions to be implemented by the farmer to decrease impacts of the farming system on freshwater (Ministry for the Environment, 2023). The FWFP takes into account Catchment Context Challenges and Values (CCCV) and all on-farm 'actions' need to address both the regulatory requirements and also the identified CCCVs. For hill country farms, FWFPs will help identify and tackle land management issues, such as soil erosion and CSAs, and identify management strategies such as space-planted trees, riparian planting and CSA management to reduce losses of contaminants to waterways. Although not compulsory under FWFPs, the use of nutrient budget models such as OverseerFM would also benefit farm nutrient management.

Since FWFPs are compulsory for almost all farms, they are likely to have positive impacts at the catchment scale. An integrated catchment management project aimed at achieving economic and environmental benefits at the Whatawhata Hill Country Research Centre (Dodd, Quinn, et al., 2008; Dodd et al., 2008, 2008b) found that implementing catchment land use changes which involved tree planting, riparian fencing, changes in livestock type and numbers resulted in significant improvements in stream water quality (i.e., reductions in loads of sediment, total N and P, and levels of faecal coliforms), and a per hectare increase in beef and lamb production within a period of about 4 years. The nonsignificant changes in nitrate losses observed in this Whatawhata study were catchment-specific and likely associated with nitrate reserves in groundwater, which meant that a longer monitoring time was required to observe the impact of the management strategy on nitrate losses to surface water. It also highlights the need for plans, specifically geared towards achieving freshwater quality, to focus on understanding the farm/catchment's natural features, including geology and soil types, as these strongly influence nitrate transport from agricultural systems to receiving waters (Burkitt & Bretherton, 2022). Such integrative management approaches that consider not only the economic and environmental gains but also the social and ecological needs of the area have been recommended in similar agricultural landscapes in Scotland, England and Ireland (Costello, 2020; Hanley et al., 2008; Short & Dwyer, 2012).

## 4 | CONCLUSIONS

Pastoral hill country farm practices that involve greater nutrient input into the soil (e.g., high fertiliser application rates and cattle grazing relative to sheep grazing) increase nitrate losses from pastoral hill

country especially from lower slope areas. Precision fertiliser application on hill country farms (through tested strategies such as variable rate fertiliser applications) and reducing cattle-to-sheep ratios are effective means of limiting nitrate losses from pastoral hill country farms. Pastoral hill country landscape features, combined with grazing practices, can lead to variable runoff and nutrient loss rates from CSAs. Protecting CSAs during grazing activities could mitigate nutrient losses to receiving waters. Carrying out intensive farm practices such as winter cropping or cattle supplement feeding on imperfectly drained soils potentially result in greater sediment and nutrient losses, including nitrate loss, via surface runoff. Nitrate losses would likely be limited if such practices are done on well-drained soils with high subsurface denitrification capacity. Detailed mapping of hill country soils and topography to inform the strategic placement of cropping and grazing could help reduce potential nutrient losses.

Hill country seepage wetlands play an important role in reducing nitrate losses to receiving waters, especially during low flow periods. Adequate management of seepage wetlands to improve their nitrate attenuation capacity, conversion of pasture to native forest and riparian management are viable management options for reducing nitrate losses from pastoral hill country. Further research and integration of hill country landscape features and their management into FWFPs, which incorporates the local geology, soil types and complex topography within hill country farms, would help identify actions which mitigate nitrate loss for improved water quality. Finally, integrative long-term studies involving both air and water quality assessments (nitrate leaching and runoff losses, and nitrous oxide emissions) would provide a thorough understanding (and broad-scale management) of the effects of pastoral hill country landscape features and land management practices on N dynamics, in order to achieve better environmental outcomes.

### AUTHOR CONTRIBUTION

All authors contributed to manuscript writing, which was led by Grace Chibuike.

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The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

### ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.



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## APPENDIX

**TABLE A1** NZ hill country original research studies<sup>a</sup> related to soil N dynamics and its impact on environmental quality.<sup>b</sup>

Landscape feature/ practice	Environmental focus	Study scale	References <sup>c</sup>
Land management	Water quality	Field	Morton and Stevens (2023)
	Water quality	Field	Mackay-Smith et al. (2022)
	Water quality	Laboratory	Chibuike et al. (2021)
	Water quality	Field	Chibuike, Burkitt, Camps-Arbestain, et al. (2019)
	Water quality	Modelling	Vogeler et al. (2017)
	Water quality	Field	Hoogendoorn et al. (2017)
	Water quality	Field	Scott et al. (2015)
	Air quality; Water quality	Modelling	Hoogendoorn, Bowatte, et al. (2011)
	Air quality; Water quality	Laboratory	Dodd and Mackay (2011)
	Air quality	Field	Letica et al. (2009)
	Water quality	Field	Parfitt et al. (2009)
	Water quality	Laboratory	Hoogendoorn, Devantier, et al. (2008)
	Air quality	Field	Hoogendoorn, de Klein, et al. (2008)
	Water quality	Field	Dodd, Quinn, et al. (2008)
	Water quality	Field	Dodd et al. (2008a)
	Water quality	Field	Dodd et al. (2008b)
Water quality	Field	Betteridge et al. (2007)	
Water quality	Field	McDowell (2006)	

**TABLE A1** (Continued)

Landscape feature/ practice	Environmental focus	Study scale	References <sup>c</sup>
	Water quality	Field	Quinn and Stroud (2002)
	Air quality; Water quality	Laboratory	Hawke (2001)
	Air quality; Water quality	Laboratory	Davis (2001)
	Water quality	Field	Quinn et al. (1997)
	Air quality; Water quality	Laboratory	Lambert et al. (1996)
	Water quality	Field	Williamson et al. (1996)
	Air quality; Water quality	Laboratory	Ross, Speir, Kettles, Tate, et al. (1995)
	Air quality; Water quality	Laboratory	Ross, Speir, Kettles, Tate, et al. (1995)
	Water quality	Field	Sakadevan et al. (1993c)
	Air quality; Water quality	Laboratory	Jiayou et al. (1993)
	Air quality; Water quality	Laboratory	Mackay et al. (1991)
	Water quality	Field	Cooper and Thomsen (1988)
	Water quality	Field	Cooper et al. (1987)
	Water quality	Field	Cooper (1986)
	Water quality	Field	Lambert et al. (1985)
	Water quality	Field	McColl and Gibson (1979a)
	Water quality	Field	McColl and Gibson (1979b)
	Water quality	Field	Bargh (1978)
	Water quality	Field	McColl et al. (1977)
Land management and Seepage wetland	Water quality	Field	Black et al. (2015)
Land management and Soil type	Water quality	Field	Burkitt et al. (2017)
	Water quality	Field and Modelling	Burkitt et al. (2016)
	Water quality	Field	Fransen et al. (2023)
Land management and Topography	Air quality	Laboratory	Zhong et al. (2016)
	Water quality	Field	Hoogendoorn et al. (2016)
	Water quality	Field	Bunyaga et al. (2023)
	Air quality; Water quality	Modelling	Bilotto et al. (2022)
	Air quality; Water quality	Laboratory	Mackay, Vibart, McKenzie, Devantier, et al. (2021)
	Air quality; Water quality	Laboratory	Mackay, Vibart, McKenzie, Costall, et al. (2021)
	Air quality; Water quality	Laboratory	Schipper et al. (2011)
	Water quality	Field	Crofoot et al. (2010)
	Water quality	Field	Puha et al. (2008)
	Air quality; Water quality	Modelling	Bowatte et al. (2006)
	Air quality; Water quality	Laboratory	Letica et al. (2006)
	Air quality; Water quality	Laboratory	López et al. (2003)
	Air quality; Water quality	Laboratory	Lambert et al. (2000)
	Water quality	Field	Nguyen et al. (1998)

(Continues)

**TABLE A1** (Continued)

Landscape feature/ practice	Environmental focus	Study scale	References <sup>c</sup>
	Water quality	Laboratory and Field	Sakadevan et al. (1994)
	Water quality	Field	Sakadevan et al. (1993a)
	Air quality; Water quality	Laboratory	Sakadevan et al. (1993b)
	Water quality	Field	Sakadevan et al. (1993d)
	Air quality; Water quality	Laboratory	Sheath and Boom (1985)
	Air quality; Water quality	Laboratory	Ledgard et al. (1983)
	Air quality; Water quality	Laboratory	Ledgard et al. (1982)
Seepage wetland	Water quality	Field	Sanwar et al. (2022)
	Water quality	Laboratory	Chibuike et al. (2020)
	Water quality	Field	Burkitt et al. (2015)
	Water quality	Field	McKergow et al. (2012)
	Water quality	Field	Rutherford et al. (2009)
	Water quality	Field	Rutherford and Nguyen (2004)
	Water quality	Field	Burns and Nguyen (2002)
	Water quality	Laboratory	Matheson et al. (2002)
	Water quality	Field	Cooper (1990)
	Water quality	Field	Cooke and Cooper (1988)
	Water quality	Field	Cooper and Cooke (1984)
Soil type	Air quality; Water quality	Laboratory	Schipper et al. (2014)
	Air quality	Field	van der Weerden et al. (2011)
Topography	Air quality	Field	Luo et al. (2019)
	Air quality	Field	Carlson et al. (2016)
	Air quality	Modelling	Saggar et al. (2015)
	Water quality	Field	Hoogendoorn et al. (2014)
	Air quality; Water quality	Laboratory	Parfitt et al. (2013)
	Air quality; Water quality	Laboratory	Devantier et al. (2012)
	Water quality	Field	Hoogendoorn and Devantier (2011)
	Air quality; Water quality	Laboratory	Schipper et al. (2010)
	Water quality	Modelling	Bidwell et al. (2008)
	Water quality	Field	Smith (1989)
	Water quality	Field	Smith (1987)
	Air quality; Water quality	Field	Lambert and Roberts (1978)
Topography and Soil type	Water quality	Laboratory	Chibuike, Burkitt, Bretherton, et al. (2019)
	Air quality	Field	Luo et al. (2013)

<sup>a</sup>Studies available online (Scopus and other websites) as of 15 May 2023. Literature search on Scopus was done via the advanced search option using the keywords 'hill country' AND 'New Zealand' AND 'nitrogen' OR 'nitrate' OR 'nitrous oxide' AND 'water quality' AND 'air quality'. Other relevant online publications such as conference/workshop proceedings not available on Scopus were also searched and collated. After duplicate removal, the studies were screened to include only original research studies (conducted on NZ pastoral hill country landscapes) that measured a form of N, for example, nitrate or nitrous oxide in soil, water and/or air samples. Grey literature such as commissioned reports, theses, and book chapters were excluded.

<sup>b</sup>Although some studies did not focus on environmental quality, they are included in this table if they measured a form of soil N in the laboratory after treatment application and/or soil sampling (this approach was adopted to gain a better understanding of N dynamics in NZ pastoral hill country). For such studies, the 'environmental focus' is reported as both air and water quality unless otherwise specified.

<sup>c</sup>See main article for reference list.