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Research article

Soil nutrient enrichment in pastoral systems through shelterbelts

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ABSTRACT

Shelterbelts along pasture boundaries are a natural, cost-effective, and sustainable solution to environmental challenges such as soil degradation and nutrient losses in New Zealand's pastoral systems. However, there's limited information on how shelterbelts affect nutrient dynamics in neighbouring pasture soils.

Three field study sites, two dairy farms and one beef and sheep farm, consisting of the same soil type, were selected. Shelterbelts on the sites were composed of Pinus or Macrocarpa, or a mix of Macrocarpa and Willow. Soil samples were collected from each site, both with and without shelterbelts, at three transects for six distances (1 m, 5 m, 10 m, 20 m, 40 m, 80 m) and two soil depths (0–7.5 cm and 7.5–15 cm) in late spring 2023.

Shelterbelts on all four farms significantly affected soil nutrient distribution in the adjacent area. Soils within 10 m of shelterbelts had higher total and Olsen phosphorus levels by up to 65 % and 80 %, respectively; the total and nitrate nitrogen levels increased by up to 64 % relative to control (no shelterbelt) soils. Shelterbelts increased soil organic carbon by up to 75 %. The macrocarpa and willow combined shelterbelt deposited around 17 Mg more C in the area tested compared to the control. These findings indicate that the shelterbelt with grazed pastures enhances phosphorus and nitrogen availability within the immediate vicinity. The inclusion of diverse species can contribute to the accumulation of topsoil carbon. Future research should focus on comparing more diverse tree species and improved grazing practices within shelterbelts to enhance the sustainability of the grazing farming system.

1. Introduction

New Zealand (NZ) is renowned for its rich pasture-based agriculture systems, primarily serving as the backbone of its economy (Caradus et al., 2023). About two-thirds of the land area in NZ has undergone a land use change, mainly from natural forests to pasture (Hewitt et al., 2021). The total land use for pasture production occupies 97,500 km^2, accounting for 39 % of the total land availability in NZ (Rys et al., 2021), and is predominantly based on perennial ryegrass and white clover mix (Cardozo et al., 2018). Rapid expansion in pastoral agriculture in the dairy industry produces a 15–18 % increase in export income yearly and raises the number of dairy cows by 50 %, from about 2.40 million to 4.78 million from 1990 to 2013, and since that time, dairy cattle number have been slightly fallen by 12 % (Dairy NZ, 2023).

While agricultural intensification has brought financial benefits and prosperity to NZ, it has also given rise to several environmental challenges, including soil degradation, nutrient leaching, runoff, and gaseous losses (Gray et al., 2021; Hoogendoorn et al., 2011; Houlbrooke et al., 2011; Soliman and Walsh, 2005). Addressing these challenges while also balancing increased agricultural productivity to meet export demands, reducing greenhouse gas emissions, and implementing regulations to improve freshwater quality (Adam et al., 2017; Cochrane et al., 2022; Rae et al., 2008) requires innovative approaches to sustainable farming practices and environmental management. Therefore, the agriculture sector in NZ has been implementing various management strategies such as stand-off pads (Fenton, 2012), soil chemical amendments (Di and Cameron, 2002), reduced chemical fertiliser use (Beukes et al., 2024), and inclusion of diverse pastures (Vogeler et al., 2017). However, adaptation of existing mitigation options is intensive and involves capital investment by farmers for implementation (Beukes et al., 2011). Hence, researchers are constantly seeking mitigation strategies that are cost-effective and easy to adapt and implement on a mass scale.

Planting trees on farms is one such option to control environmental losses using natural resources. There are various ways to include trees on farms, planted as shelterbelts, alleys, scattered or riparian buffers (Fernandez and Daigneault, 2017; McAdam et al., 2006). Shelterbelts, in particular, are rows of trees or shrubs planted along the boundaries of

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agricultural fields or pastures to serve as a barrier against severe winds, and heavy rain for the soil, grazing animals, and pastures (Brandle et al., 2004; Gregory, 1995; Hawke et al., 1999; Mize and Brandle, 2008; Rutigliano et al., 2023). The microclimatic environment created by shelterbelts alters the temperature and humidity of neighbouring land, increasing soil moisture and activating the soil nutrient cycle and microbial activity (Kort, 1988a; Scholten, 1988).

Shelterbelts offer numerous environmental benefits, including carbon (C) sequestering in their woody biomass and soil, enhancing nutrient availability, and fostering soil microbial diversity (Chen et al., 2021). Additionally, shelterbelts have the potential to influence these soil properties through various mechanisms, including modification of microclimate conditions and interception of nutrients from surface runoff and groundwater. These effects can improve soil structure, water retention, and nutrient cycling, ultimately benefiting agricultural productivity and environmental quality (Jeyakumar et al., 2014; Wojewoda, 2003).

Shelterbelts are mainly used in NZ to provide shelter to livestock from severe weather and protect soil from erosion by wind and water. Despite their potential benefits, there is limited information on the specific effects of shelterbelts on soil nutrient dynamics in NZ pastoral systems. This knowledge gap hinders information transfer to farmers and the development of evidence-based recommendations to integrate shelterbelts into farm management practices. The objective of this present study is to investigate whether there is any significant difference in key soil nutrient distribution in shelterbelts compared to pastures without shelterbelts (control).

A field study was conducted in the Manawatu region in the North Island of NZ to investigate the influence of coniferous shelterbelts on soil nutrient status in grazed pasture systems. The study was based on the hypothesis that the nutrient availability would be higher in the soil closer to shelterbelts than in the neighbouring pasture soils. The present study builds and contributes to the growing knowledge of sustainable farming practices in temperate regions by examining the influence of shelterbelts on soil nutrient dynamics. Further, it aims to provide valuable insights for farmers, policymakers, and researchers striving to enhance the resilience and sustainability of pastoral systems in New Zealand.

2. Study site and research methods

2.1. Sampling sites, soil sampling, experimental design, and soil analysis

Three research sites (Glen Oroua dairy farm, Massey dairy farm-4, and Massey Tuapaka beef and sheep farm) were selected in the Palmerston North, Manawatu region in NZ (Fig. 1). All these selected farms are commercially operated for milk and meat production. White clover and perennial ryegrass are the major pasture plant species renewed every 5–10 years (Table 1). Four shelterbelts were included in the present study, each occupying approximately 1–2 % of the total paddock grazing area. A single shelterbelt was selected from each of the Massey dairy farm-4 and Glen Oroua dairy farm, each featuring a distinct tree species. In contrast, two shelterbelts, each comprising a different tree species, were selected from Massey University's Tuapaka beef and sheep farm (Table 1). Both Massey dairy farm-4 and Glen Oroua dairy farm shelterbelts were more similar, with trees over 20 years old and heights of approximately 14 m. The Massey dairy Farm-4 shelterbelt consists of 23 Pinus radiata trees (DF-P), while the Glen Oroua dairy farm shelterbelt has 24 Macrocarpa trees (DF-M). The beef and sheep farm at Massey Tuapaka shelterbelt featured more mature trees at 26 years of age, including one shelterbelt with 24 Macrocarpa and Willow (BS-MW) and another shelterbelt with 24 trees of Pinus radiata (BS-P), all of which were approximately 18 m tall.

The three study sites had different fertiliser and grazing management. Two dairy farms applied nitrogen (100–150 kg/ha/yr), phosphorus (30–125 kg/ha/yr), potassium (30–50 kg/ha/yr), and sulphur (20–37 kg/ha/yr) at a stocking rate of 2.6–3.0 cows/ha with a 21–45 day rotational grazing system. Tuapaka Beef and Sheep farm applied the least fertiliser, with nitrogen (50–80 kg/ha/yr), phosphorus (50–125 kg/ha/yr), potassium (76 kg/ha/yr), and sulphur (75 kg/ha/yr). They managed 4.5–5.0 ewes and 2.3–2.6 cows/ha with a hill-country adaptive rotation system, with longer grazing intervals of 24–32 days in summer and 40–50 days in winter. (Table S1).

2.2. Collection of soil samples

Soil samples were collected from each paddock, both with and without shelterbelts (control paddock), along three transect lines from

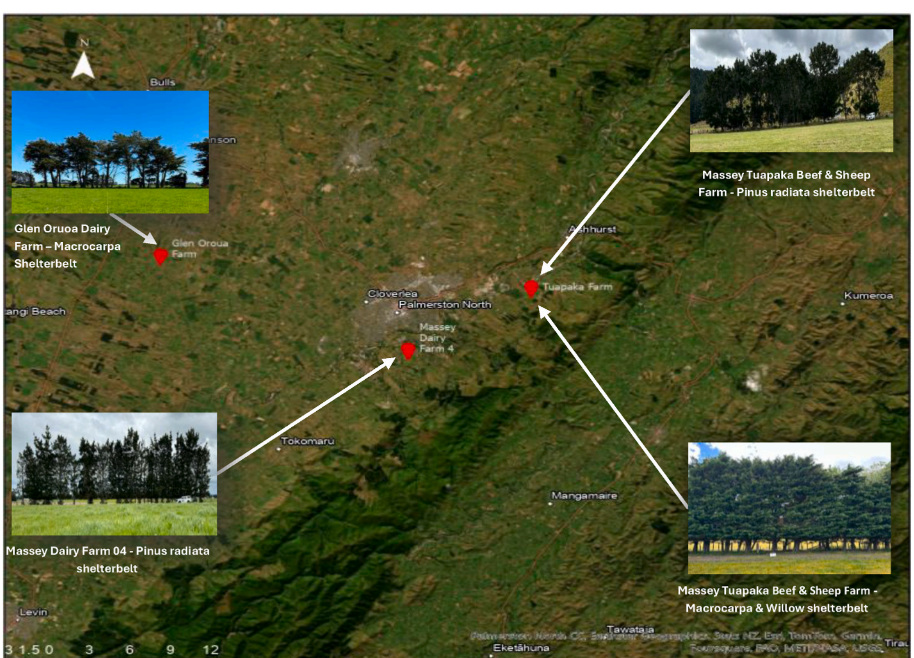

Fig. 1. Location of the study and the three sampling sites used in this study.

Table 1
Details of the sampling sites and shelterbelts.

Site	Glen Oroua farm	Massey dairy farm - Four	Massey Tuapaka farm	
Species	Macrocarpa	Pinus radiata	Macrocarpa & Willow	Pinus radiata
Location	−40.3221562, 175.4008839	−40.3973688, 175.6202590	−40.3421806, 175.7257678	
Avg. Rainfall (mm)	720	980	1100	
Avg. Temperature (°C)	10 to 22	7 to 18	7.5 to 17.5	
Age (Years)	>20	>20	26	26
Height (m)	13.9	13.5	18.2	18.2
No. of live trees	24	23	24	24
Land Use	Dairy	Dairy	Beef and Sheep	
Farm Code	DF-M	DF-P	BS-MW	BS-P

the fence at 1 m, 5 m, 10 m, 20 m, 40 m, and 80 m (Fig. 2). These distances were determined as five times the average tree height (5H) (Sun et al., 2022; Zheng et al., 2016). Sampling was conducted at two soil depths: 0–7.5 cm (surface soil) and 7.5–15 cm (sub-surface soil) at the end of November 2023, representing the spring.

For each transect, ten soil cores (25 mm diameter and 150 mm long) within a 1-m radius were taken at each distance and split into 0–7.5 cm and 7.5–15 cm soil depths, respectively. Each replicate soil sample was then homogenised to make a composite soil sample, which was stored for the subsequent analysis. Samples were then sieved to 2 mm, and a portion of the sieved soil samples was stored at 4 °C for wet soil physicochemical analyses; the remaining samples were air-dried in a ventilated room until they reached a constant dry mass for dry soil physicochemical analyses.

2.3. *Soil physicochemical analysis*

Soil samples were analysed for their physicochemical properties using standard laboratory protocols. Gravimetric soil water content was determined by measuring the weight loss of farm-fresh soil as it dried overnight in an oven at 105 °C. Soil pH was analysed in a 1:2.5 ratio of soil to water mixture using a pH meter (Acumen 910, Fisher Scientific Ltd, Pittsburgh, PA, USA) (Blakemore et al., 1987). Extractable aluminium (Al), manganese (Mn), and iron (Fe) were measured using the acid ammonium oxalate extraction method (Blakemore et al., 1987), with analysis performed using a Microwave Plasma- Atomic Emission Spectrophotometer (MP-AES) (4200 MP-AES, Agilent, USA).

For mineral N measurement, soil extracted to 2 M KCl 1: 5 ratio and calorimetrically analysed for NO_3^- - N and NH_4^+-N using the indophenol reaction with sodium salicylate and hypochlorite for NH_4^+-N and NO_3^--N by Cd reduction column from a QuikChem 8500 flow injection analyser (Beets et al., 2013; Blakemore et al., 1987). Olsen P extraction involved the phosphomolybdate method (Murphy and Riley, 1962). Soil cation exchange capacity (CEC) was determined using the semi-micro leaching method (Blakemore et al., 1987), and the extractants were analysed by MP-AES (4200 MP-AES, Agilent, USA). Total nitrogen (TN) and total phosphorus (TP) were determined using a 4 ml digest mixture (K_2SO_4, selenium powder, and H_2SO_4) and 1 g of air-dried soil (<2 mm) heated for 4 h and then topped up to 50 ml until a clear solution and measured on an autoanalyser (Blakemore et al., 1987). The dry combustion method determined the total carbon (TC) content using a Vario Elementar C, H, N, and S analyser (Vasylivna et al., 2021).

2.4. *Statistical analysis*

The data was tested for normality to ensure the appropriateness of subsequent statistical tests using R Studio R Session 4.3.1 version of statistical software (R Core Team, 2023). The effects of shelterbelts on

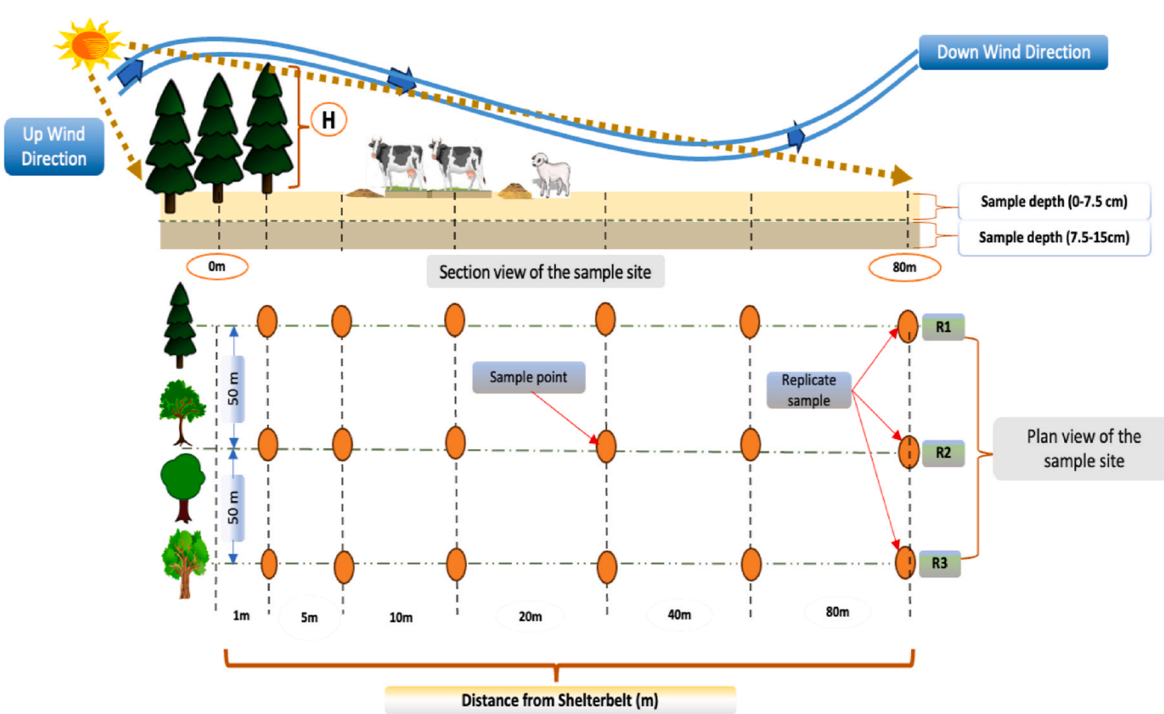

Fig. 2. The design of soil sample collection in the shelterbelt paddock.

soil properties were assessed using a two-way analysis of variance (ANOVA) test, which examined the influence of shelterbelt presence (SB), sampling distance (D), and their interaction (SB*D) for two soil depths (0–7.5 cm and 7.5–15 cm) (Table S2). A post-hoc test was conducted to identify the differences between treatment means of shelterbelt presence and control for each distance for each farm separately using Duncan's multiple range test (DMRT).

Data preprocessing was performed using the R software built-in packages of dplyr, which provided efficient data transformation and summarization tools. The ggplot2 package in R was employed for data visualization to create informative and visually appealing graphs. Principal Component Analysis (PCA) was conducted for each farm with and without a shelterbelt to analyse the complex interactions between soil chemical properties and their response to the presence of shelterbelt and control using the FactoMineR package, with the factoextra package facilitating the visualization of PCA results (Dennis da Silva Ferreira et al., 2023).

3. Results

3.1. *Effect of shelterbelt and sampling distance on soil properties in surface and sub-surface soils in each farm*

3.1.1. *Dairy farm with macrocarpa shelterbelt (DF-M)*

The presence of soil nutrients was consistently higher in the shelterbelt samples than in control plots. However, the influence of the shelterbelt on each soil nutrient varied with the distance of the shelterbelt. Generally, concentrations of soil nutrients were higher in soils collected closer to the shelterbelt (10 m) than in the soils collected away from the shelterbelt (80 m) or in the control soils. The influence of the shelterbelt through the distance was more pronounced for Olsen P, NO_3^--N, CEC, and TC. Olsen P, NO_3^--N and TC at 5 m from the shelterbelt were approximately twice as high as 1 m and gradually decreased with increasing distance up to 80 m (Fig. 3a, b, c). CEC was higher at 1 m distance and gradually decreased by 1.8 times when moving to 80 m from the shelterbelt (Fig. 3e). In contrast, there was less NH_4^+-N closer to the shelterbelt, and the amount of NH_4^+-N increased with increasing distance from the shelterbelt beyond 10 m (Fig. 3d). However, these changes were not significant. No significant effect of the shelterbelt or sampling distance was observed for soil pH, TP, or TN (Table S2).

A similar effect was observed in the subsurface samples. Soil properties such as Olsen P, NO_3^--N, and TN were significantly ($p < 0.05$) higher in the shelterbelt than in the control paddock at least up to 5 m distance. The values were 3 times, 2.8 times, and 1.3 times higher, respectively, closer to the shelterbelt (5 m) (Fig. S1). The Olsen P and TN decreased beyond this distance, and the NO_3^--N also declined, but did not exhibit a definite trend. The remaining soil parameters, pH, TC, CEC, and TP, showed no significant differences in the presence of the shelterbelt or distance (Table S2).

To investigate the interaction of soil properties with the shelterbelt, the PCA plot (Fig. 7, A-1and A-2) of the surface soil and subsurface soil of DF-M was produced. In surface soil of the shelterbelt showed strong and significant ($p < 0.001$) positive correlations along Dim1 for Olsen P (Pearson R: 0.78, p-value: <0.001), N-NO_3 (Pearson R: 0.82, p-value: <0.001), CEC (Pearson R: 0.82, p-value: <0.001), and the control paddock was positively associated with TP (Pearson R: 0.68, p-value: <0.001), Mn (Pearson R: 0.82, p-value: <0.001), and pH (Pearson R: 0.72, p-value: <0.01) which loaded on Dim2. The segregation of groups was the same in the subsurface soil, but it overlapped slightly compared to the surface soil. The impact of the shelterbelt on subsurface soil remains more similar to that of surface soil, except for TC, which decreased with depth.

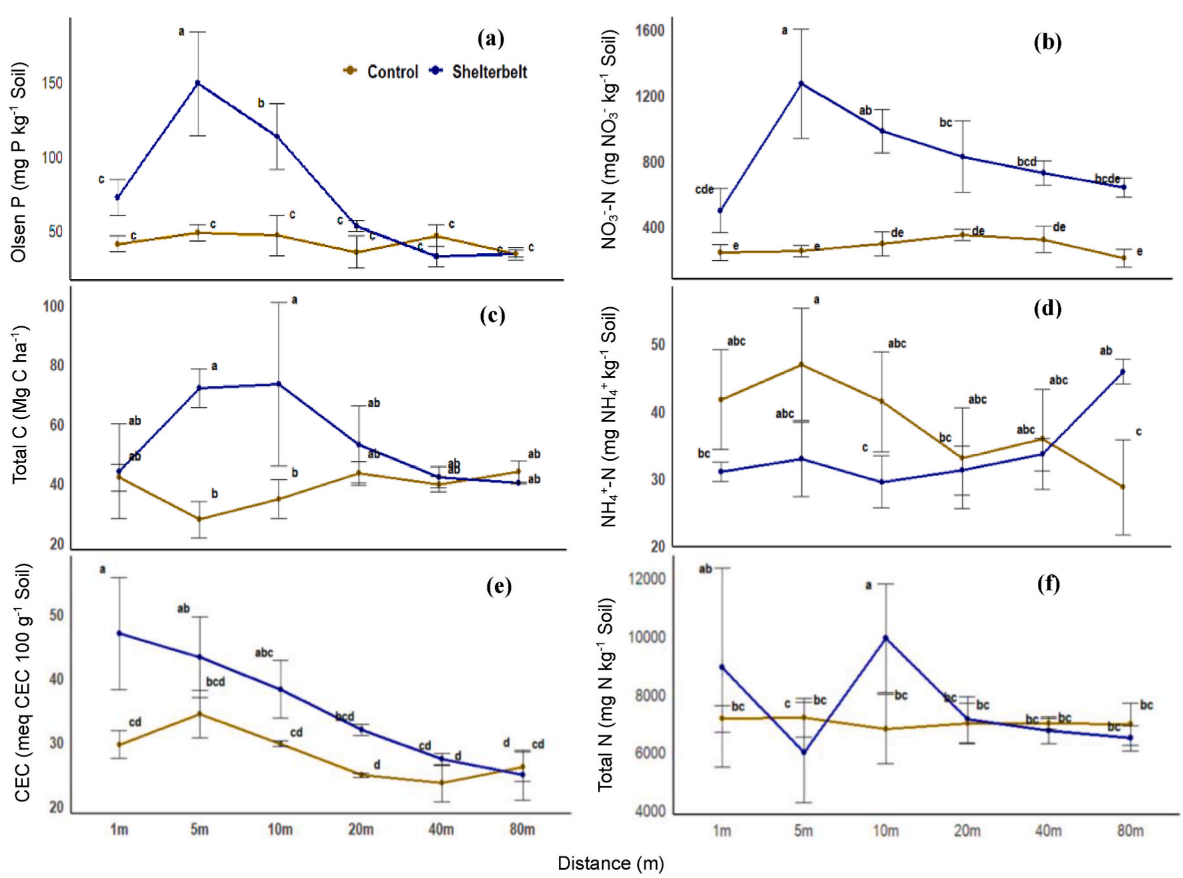

Fig. 3. Variation of soil chemical properties in the surface soil in a Dairy farm Macrocarpa shelterbelt.

3.1.2. Dairy farm with pine shelterbelt (DF-P)

The soil in the shelterbelt paddock had consistently higher availability of soil nutrients such as Olsen P, NO_3^--N, and NH_4^+-N than the control paddock. Soil Olsen P, TC, TN, and TP were significantly ($p < 0.05$) higher in the shelterbelt up to 5 m and NO_3^--N was up to 10 m compared to the control plot (Fig. 4a, b, c, f). No significant effect of the shelterbelt or sampling distance was observed for soil NH_4^+-N and pH (Table S2).

Similar to the surface samples, the shelterbelt's presence significantly ($p < 0.05$) influenced soil Olsen P, NO_3^--N, NH_4^+-N, TC, and TN compared to the control in the subsurface soil. The NO_3^--N and TN were decreased by 28 % and 43.7 %, respectively, from the 1 m proximity to the 80 m distance in the shelterbelt (Fig. S2). However, at a 5 m distance, NO_3^--N was the highest by 44.6 % compared to the 1 m distance from the shelterbelt (Fig. S2). In contrast, NH_4^+-N was lower under the shelterbelt and increased with distance by 11.2 % (Fig. S2) from 1 m distance to 80 m in the shelterbelt, and observed a 27.8 % increase of NH_4^+-N compared to the surface soil. The remaining soil parameters, pH and TP, showed no significant differences in the presence of the shelterbelt or distance (Table S2).

Based on the PCA (Fig. 7, B-1 and B-2), the shelterbelt demonstrates increased nutrient retention and availability, particularly for Olsen P (Pearson R: 0.87, *p*-value: <0.001), TP (Pearson R: 0.93, *p*-value: <0.001), and TN (Pearson R: 0.93, *p*-value: <0.001), and CEC (Pearson R: 0.89, *p*-value: <0.001) along Dim1 in surface soil. Compared to surface soil, subsurface soil Olsen P and CEC in the shelterbelt were diminished and clustered in the control plot, indicating no influence from the shelterbelt. Further, the variation in the availability of micronutrients such as Al (Pearson R: 0.79, *p*-value: <0.001) and Fe (Pearson R: 0.62, *p*-value: <0.001) along Dim1 suggests a negative correlation with shelterbelt and the composition of the parent material may play a role in determining soil characteristics.

3.1.3. Beef and sheep farm with macrocarpa and willow shelterbelt (BS-MW)

Similar to the effect of shelterbelt on the dairy farm, on the beef and sheep farm, we observed higher soil nutrient content in the soils collected from the paddock with shelterbelt than the paddock with no shelterbelt. Although soil nutrient availability was higher in the shelterbelt paddock, Olsen P, NO_3^--N, CEC, TC, TN, and TP were more available within 5 m of the shelterbelt with higher significant ($p < 0.05$) concentrations than the control plot. For example, Olsen P and NO_3^--N were 2.6 and 3.7 times higher than the control sample at 1 m from the shelterbelt and decreased steeply up to 10 m (Fig. 5a and b). Total carbon was observed to be 2.4 times higher at 1 m from the shelterbelt, decreasing from 71.8 (1 m) to 49.5 (80 m) Mg C ha^{-1}, but throughout the distance, soil C content remained significantly higher ($p < 0.05$) in the shelterbelt plot compared to the control, (Fig. 5c). The percentage decrease in the CEC, TP, and TN with increasing distance (1 m–80 m) from shelterbelts were 34.7 %, 18.2 % and 36.9 %, respectively, except at 5 m distance for TP and TN, increased by 13.5 % and 5.9 %, respectively 1 m from the shelterbelt (Fig. 5, f). No significant effect of the shelterbelt or sampling distance was observed for soil pH and NH_4^+-N (Table S2).

Like surface soil, sub-surface soil in the shelterbelt significantly ($p < 0.05$) influenced TC and TN up to 5 m and TP up to 20 m compared to the control. The effects of the shelterbelt were most pronounced in soil collected closer to the shelterbelt and decreased with increasing distance. However, at a 5 m distance, CEC was measured to be the highest by 6.3 % compared to the 1 m distance (Fig. S3). In contrast, TN was lower under the shelterbelt and increased with distance by 40.6 % at 80 m (Fig. S3). The remaining soil parameters, pH and NH_4^+-N, showed no

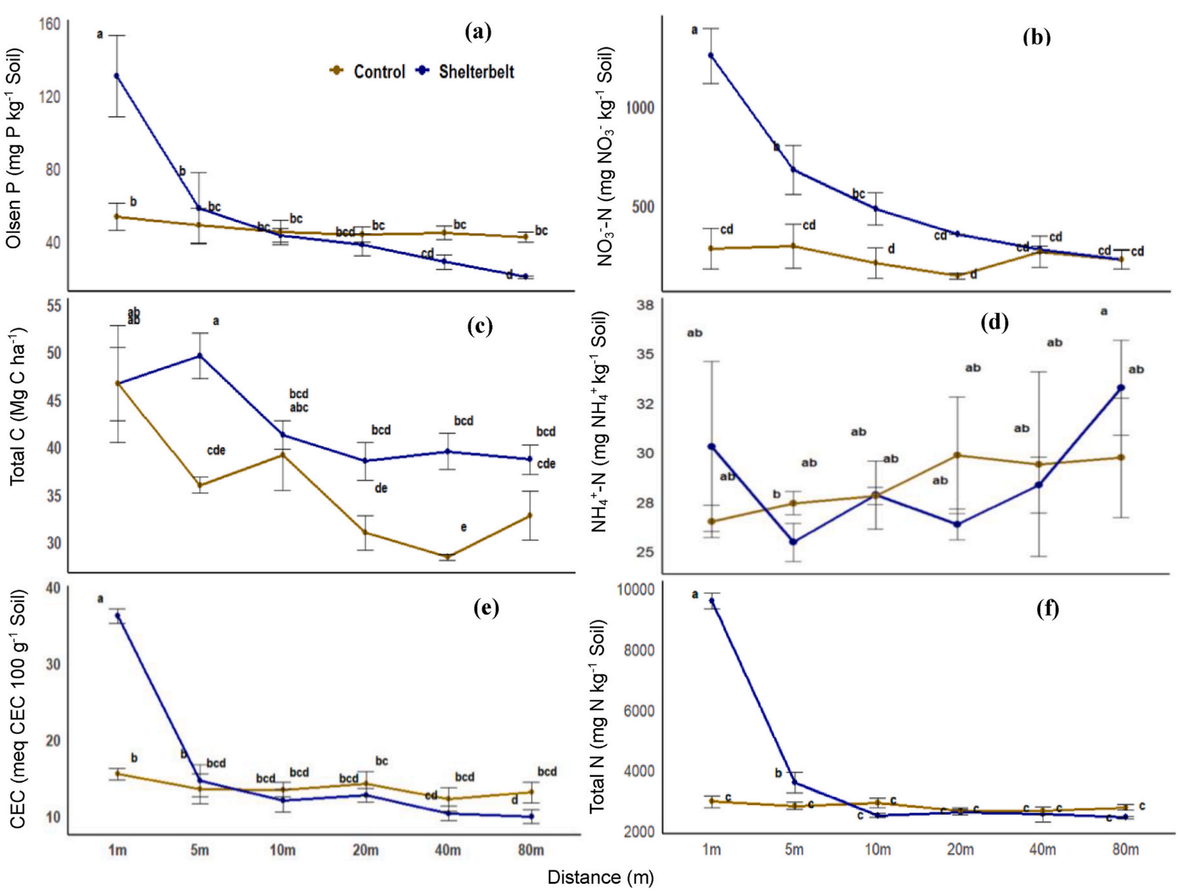

Fig. 4. Variation of soil chemical properties in the surface soil in a Dairy farm Pinus radiata shelterbelt.

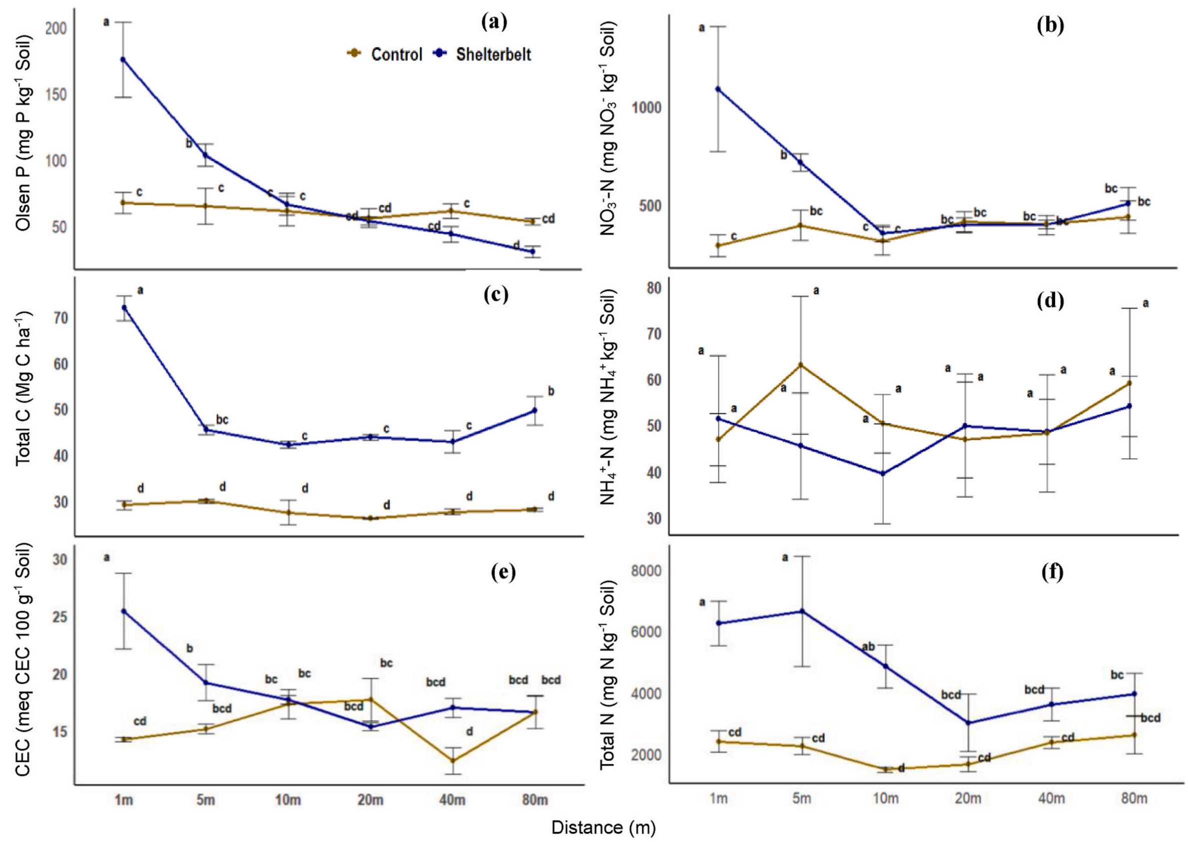

Fig. 5. Variation of soil chemical properties in the surface soil in a Beef and Sheep farm, Macrocarpa & Willow shelterbelt.

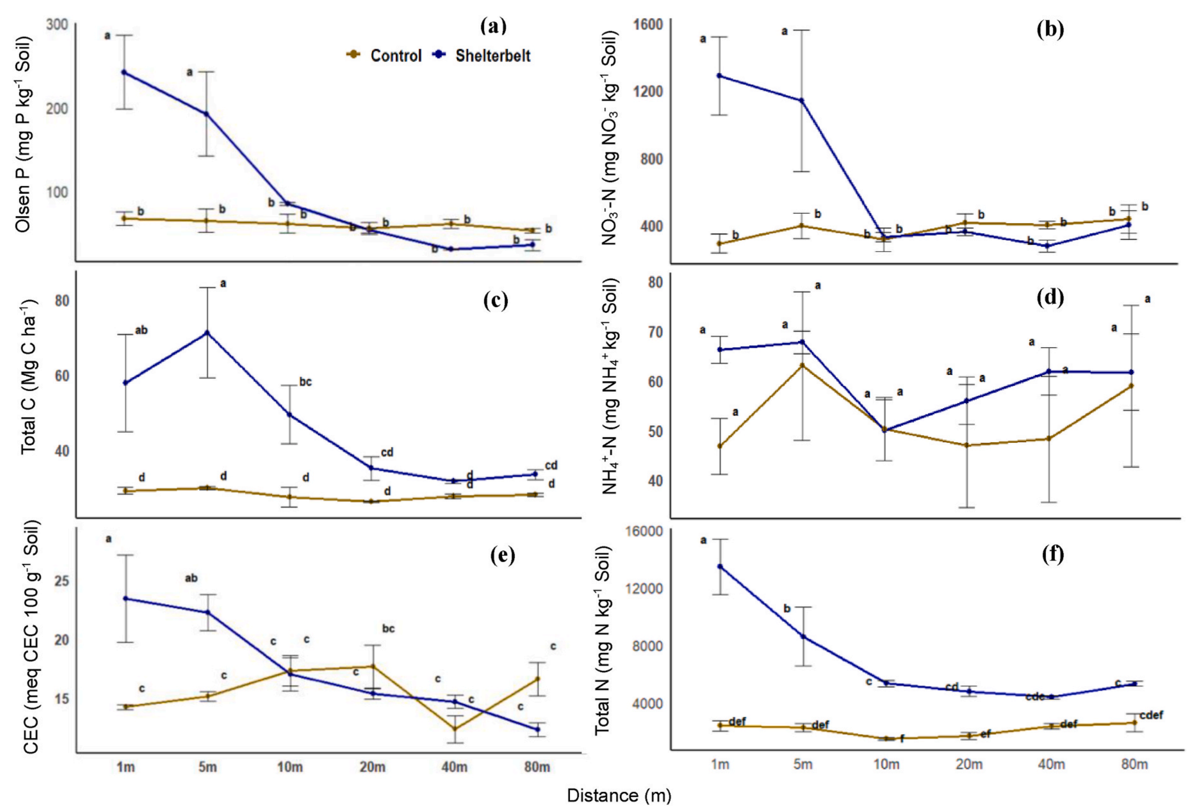

Fig. 6. Variation of soil chemical properties in the surface soil in a Beef and Sheep farm, Pinus radiata shelterbelt.

significant differences in the presence of the shelterbelt or distance (Table S2).

The PCA (Fig. 7, C-1 and C-2) of the BS-MW shelterbelt substantially enhances most soil properties such as Olsen P (Pearson R: 0.70, *p*-value: $<$0.001), NO_3^--N (Pearson R: 0.78, *p*-value: $<$0.001), TN (Pearson R: 0.82, *p*-value: $<$0.001), TC (Pearson R: 0.87, *p*-value: $<$0.001), and CEC (Pearson R: 0.76, *p*-value: $<$0.001), irrespective of soil depth along the Dim1. Additionally, organic matter accumulation at both soil depths was highly apparent in the shelterbelt.

3.1.4. Beef and sheep farm with pine shelterbelt (BS-P)

Similar to BS-MW, soil chemical properties showed spatial variation with distance from the shelterbelt for pH, Olsen P, NO_3^--N, CEC, and TP. Further, Olsen P, NO_3^--N, CEC, TC, TN, and TP influenced the availability of soil chemical properties and were significantly higher ($p < 0.05$) than the control plot at least up to 5 m. Soil Olsen P (2.6–3.3 times) and NO_3^--N (3–3.5 times) were significantly ($p < 0.05$) higher than the control within the 1 m–5 m of the shelterbelt, then it dropped at 10 m and reached the same level as the control (Fig. 6a and b). The spatial variation of the shelterbelt was more pronounced in soil collected closer to the shelterbelts and reduced with increasing distance. The percent decrease in the soil properties with increasing distance from shelterbelts varied between the measured parameters. The Olsen P, NO_3^--N, CEC, TC, TN and TP decreased by 85.1 %, 69 %, 47.8 %, 42.2 %, 60.5 % and 60.2 %, respectively, except at 5 m distance for TC, highest by 18.9 % compared to the 1 m distance (Fig. 6c). Further, no significant effect of the shelterbelt or sampling distance was observed for soil pH and NH_4^+-N (Table S2).

Sub-surface soil in the shelterbelt significantly ($p < 0.05$) influenced Olsen P, CEC, and TP up to 10 m compared to the control. The effects of the shelterbelt were most pronounced in soil collected closer to the shelterbelt and diminished with increasing distance from 1 m to 80 m. Olsen P, TP, and CEC were decreased by 91.4 %, 60.2 % and 50.2 %, respectively, from the 1 m proximity to the 80 m distance in the shelterbelt (Fig. S4). The remaining soil parameters, pH, NO_3^--N, NH_4^+-N, TC, and TN, showed no significant differences in the presence of the shelterbelt or distance (Table S2).

According to the PCA (Fig. 7, D-1 and D-2), BS-P shelterbelt, the surface soil substantially impacted Olsen P (Pearson R: 0.68, *p*-value: $<$0.001), NO_3^--N (Pearson R: 0.67, *p*-value: $<$0.001), TN (Pearson R: 0.69, *p*-value: $<$0.001), TC (Pearson R: 0.77, *p*-value: $<$0.001), and CEC (Pearson R: 0.71, *p*-value: $<$0.001), with a strong association with the shelterbelt along the Dim1 and pH (Pearson R: 0.74, *p*-value: $<$0.001) along Dim2. Additionally, the shelterbelt moderately influenced Mn (Pearson R: 0.52, p-value: $<$0.001). Similar behaviour was observed for the soil properties in the subsurface soil compared to the surface soil.

4. Discussion

4.1. Availability of soil nutrients under different shelterbelts

All farms included in the present case study are located under similar climatic conditions on the same soil type, Tokomaru silt loam, with high clay content and poor drainage conditions (Pereira et al., 2018). The key differences among the farms are the two distinct year-round grazing systems and variation in shelterbelt species. There were remarkable differences in the distribution of soil nutrients around the shelterbelts across the farms. These differences were mainly observed in the surface soil layer (0–7.5 cm depth), whereas in the subsoil layer, the differences were either statistically non-significant or showed no clear patterns.

4.1.1. Dairy farming system

The spatial distribution of soil nutrients in dairy farms with macrocarpa shelterbelts (DF-M) reveals hotspots with Olsen P, NO_3^--N, and TC exhibiting pronounced availability at 5–10 m distances from shelterbelts. Notably, surface soils within 1–5 m of shelterbelts displayed threefold higher NO_3^--N concentrations compared to control areas, indicative of accelerated nitrification, a finding consistent with (Diana et al., 2022), who observed similar NO_3^--N enrichment and low NH_4^+-N near tree rows. This enhanced nitrification can be attributed to the interactions between soil physicochemical properties and microbial activity. Localised nitrogen inputs from livestock excreta and plant litter decomposition (Torralba et al., 2016; Udawatta et al., 2008) amplify NO_3^--N accumulation in surface soil. Despite the potential environmental concerns associated with elevated NO_3^--N concentrations, reduced water movement through soil profiles near trees may limit nitrate leaching, allowing NO_3^--N to accumulate in the upper soil layers (Qiao et al., 2016; Zhang et al., 2025). However, this phenomenon warrants further investigation to fully understand its implications for nutrient cycling and environmental sustainability in agroforestry systems (Pardon et al., 2017).

Olsen P levels were significantly elevated only at the 5–10 m distance from the shelterbelt compared to the control paddock, mirroring the spatial pattern observed for TC. Notably, TC concentrations near shelterbelts were approximately 40 % higher than those in control areas. This enrichment in soil organic carbon (SOC) likely enhances the mineralization of organic P by stimulating soil microbial activity and increasing the production of humic substances, which in turn facilitate the solubilization of organic P into plant-available forms. These findings are consistent with previous research demonstrating that shelterbelt-associated organic matter inputs, such as leaf litter and root exudates, can stimulate soil phosphatase activity, thereby accelerating the conversion of organic P to plant-available Olsen P (Acosta-Martínez et al., 2010; Lemanowicz, 2018).

In dairy farms with Pinus shelterbelts (DF-P), soil nutrient patterns were similar to those in the macrocarpa shelterbelts (DF-M) but with generally lower levels of Olsen P, NO_3^--N, TC, and CEC (Fig. S5). While nitrification in DF-P soils appears lower than in DF-M, as evidenced by 10 % higher NH_4^+-N retention in shelterbelt soil, this may be due to less NH_4^+ being either oxidized to NO_3^--N or volatilized as NH_3, leaving more residual ammonium. Unlike DF-M, TC levels under DF-P shelterbelts were not significantly higher than in control plots. This lower TC may lead to lower (SOC), thereby limiting soil microbial activity and reducing the conversion of ammonium to nitrate, resulting in more residual NH_4^+ in the surface soil. These findings suggest that the absence of higher SOC under Pinus shelterbelts could be a key factor in moderating nitrogen cycling and nutrient availability in these areas (Parfitt and Ross, 2011; Subbarao et al., 2013; Zhang et al., 2025)

4.1.2. Beef and sheep farming system

In beef and sheep farms, the mixed Macrocarpa and Willow shelterbelt (BS-MW) enhanced soil nutrient levels, showing higher Olsen P, NO_3^--N, TP, TN, CEC, up to 5 m, with TC consistently higher up to 80 m compared to control plots. The BS-MW substantially increased surface soil carbon, with TC levels 75 % higher than those in the control, extending up to 80 m. These enrichments are likely due to increased litter and decaying root inputs, reduced soil erosion, and improved nutrient cycling facilitated by tree roots and associated soil microorganisms. The composition of diverse tree species and specific farm management practices may enhance the SOC of these systems. These results are consistent with previous studies demonstrating that diverse tree plantings in agricultural landscapes can significantly enhance ecosystem services, including soil carbon storage (Carolyna et al., 2022; Zhou et al., 2022; Zhu et al., 2023). Mixed litter inputs from macrocarpa generate lignin-rich litter that slows mineralization, and willow produces high-nitrogen foliage that accelerates humification and collectively boosts SOC stocks by 12–18 % compared to mono-species shelterbelts (Dai et al., 2020; Zhang et al., 2025).

The BS-P enhanced nutrient dynamics in beef and sheep farms, where high Olsen P, NO_3^--N, TP, TN, CEC, and TC were compared to the control plot. In particular, significantly higher levels of TP and TN in BS-P surface soil were observed out of all four farms under this shelterbelt,

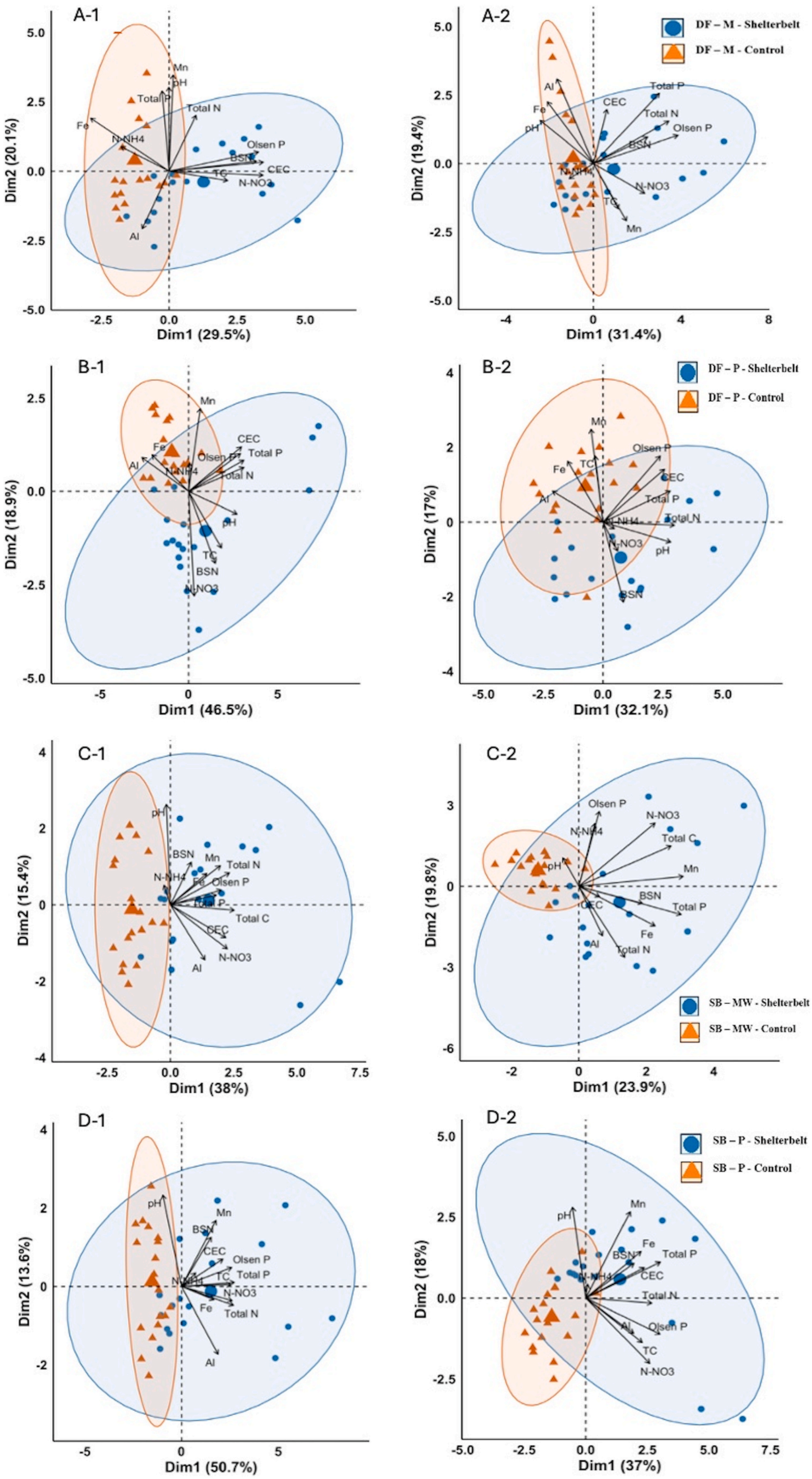

Fig. 7. PCA graph for surface and surface soil in a Dairy farm Macrocarpa (DF-M), Pinus (DF-P), Beef and Sheep farm, Macrocarpa & Willow (mixed) BS-MW) and Pinus radiata shelterbelt (BS-P).

with 239 % and 226 % increases (Fig. S5), respectively, compared to the control plot. This pronounced nutrient accumulation may be due to the interactions between tree-specific organic inputs (e.g., *Pinus* needle litter, root exudates) and reduced livestock-induced disturbance in these zones (Teo et al., 2025).

Overall, the BS-P showed higher Olsen P and NO_3^--N (76 % and 68 %, respectively) than BS-MW (30 % and 54 %) under beef and sheep farming systems. Research on Pinus radiata demonstrates that it has higher litterfall rates (258–386 g/m^2/year) and it returns significant quantities of nitrogen (1400–2400 mg N/m^2/year) and phosphorus (97–230 mg P/m^2/year) to the soil surface annually (Baker, 1983). In addition, Jeyakumar et al. (2014) demonstrated how mycorrhizal colonization in the Pinus root rhizosphere enhances its contribution to soil nutrient dynamics.

Another notable observation was the consistently higher NH_4^+-N concentrations in beef and sheep farms under pinus shelterbelts compared to those under dairy farm shelterbelts (Fig. 6d and 4d). This difference likely reflects less intensive grazing management in beef and sheep systems, where animals are more widely distributed across paddocks, resulting in more dispersed urine deposition. This, in turn, can lead to higher ammonium concentrations through urease-catalyzed hydrolysis of urea in animal urine (Jin et al., 2018; Omaliko, 1981; Sigurdarson et al., 2018).

4.2. Key findings on soil property enhancement across all shelterbelts

Four shelterbelts across all four farms reveal that the most pronounced effects for the spatial distribution of soil nutrients, particularly for Olsen P, NO_3^--N, TC, CEC, TN, and TP in the surface soil, which were consistently observed to be higher closer to shelterbelts from up to 10 m distance than control paddocks (Fig. S6) confirming our hypotheses regarding the distance-dependent effects of shelterbelts on soil properties ((Xin-Qi et al., 2015). The magnitude of these effects differs substantially between parameters in the shelterbelt. Across all four farms, TP increased by 46–65 % compared to the control, while Olsen P increased by 15–80 % (mean equivalent to 80 mg P kg^{-1} soil), exceeding the New Zealand Soil Bureau reference values (20–30 mg P kg^{-1} soil). The TN increased by 31–64 % and NO_3^--N levels in shelterbelt soils were threefold higher than those in control soils. The reason for these localized higher nutrient availability is likely driven by a cumulative process of organic matter inputs from tree litter (Hawke and Knowles, 1997; Zhang et al., 2024), livestock camping and congregation patterns (Dronen, 1988; Hawke and Dodd, 2003), and improved microclimatic conditions that enhance soil microbial activity and nutrient cycling (Liu et al., 2022; Nguyen et al., 2023). However, the increased availability of both P and N, limited to a 10 m distance, has a minimal impact on sustainable nutrient management. Factors such as stocking rate, grazing system, rotation intervals, and fertiliser management programmes can influence the enhancement of these properties in a wider area of the farming system. Hence, combining different management types with the shelterbelt composition might determine the overall improvement in the availability and retention of soil nutrients (Dhillon and Van Rees, 2016; Mize et al., 2008).

The CEC and TC in the shelterbelt paddocks were 12–26 % and 18–75 % higher than the control, respectively (Fig. S6). In particular, the SOC in the macrocarpa and willow combined shelterbelt was 75 % higher, extending up to 80 m, depositing around 17 Mg more C (assuming a 100 m length shelterbelt covering 0.8 ha) in comparison to the control. This increase (approximately 0.8 Mg C/ha/yr) was significantly higher than the expected changes recommendation highlighted by Mudge et al. (2025). They observed that the changes should be at least 0.5 Mg C/ha/yr occurring within this land use. This significant contribution from multispecies trees in a 26-year lifespan suggests that future shelterbelt management with more densely diverse species trees would enhance the sustainability of the grazing farming system.

5. Conclusions

The present study investigates the fate of soil chemical properties with a distance from four shelterbelts with varying tree species or farming systems. The study found the following observations regarding the potential use of shelterbelt paddocks for maximum productivity and reduced environmental nutrient loss:

Tree species influence nutrient availability: The significant impacts on soil chemical properties were within the 1–10 m range in the grazed pastoral systems. The impact is most notable in the surface soil, including increased Olsen P, NO_3^- -N, TN, and TP concentrations near tree lines. The Dairy Farm with Macrocarpa shelterbelt demonstrated higher availability of Olsen P and NO_3^--N near the tree line, indicating that specific tree species can influence the nutrient retention and availability patterns.

Enhanced carbon sequestration potential: The mixed-species shelterbelt with Macrocarpa and Willow on the Beef and Sheep farm showed significantly enhanced SOC throughout the entire distance, pinpointing the remarkable carbon sequestration potential associated with the diverse tree species in the shelterbelt.

Implication for nutrient management: While shelterbelts can improve soil quality and nutrient cycling, they also introduce spatial heterogeneity in the nutrient distribution in pastoral systems. This highlights the need for refined nutrient management strategies to avoid local surpluses and deficiencies, ensuring balanced fertiliser management use for optimal productivity and minimal environmental losses.

Future research should examine long-term nutrient and carbon dynamics across various tree species and soil types, and grazing management systems to optimise shelterbelt based interventions in pastoral landscapes.

CRediT authorship contribution statement

Dishan Fonseka: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Neha Jha:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Paramsothy Jeyakumar:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dishan Fonseka, Neha Jha & Paramsothy Jeyakumar reports financial support was provided by Sustainable Farming Fund by the Ministry of Business of Innovation and Employment, New Zealand. Dishan Fonseka reports financial support was provided by Massey University Doctoral Scholarship, New Zealand. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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Data availability

Data will be made available on request.

References

Acosta-Martínez, V., Bell, C.W., Morris, B.E.L., Zak, J., Allen, V.G., 2010. Long-term soil microbial community and enzyme activity responses to an integrated cropping-livestock system in a semi-arid region. Agric. Ecosyst. Environ. 137, 231–240. https://doi.org/10.1016/j.agee.2010.02.008.

Adam, D., Sandy, E., Suzie, G., Suzi, K., Edmund, L., Leah, M., Sanjay, W., 2017. Modelling the potential impact of New Zealand's freshwater reforms on land-based greenhouse gas emissions. Motu Economic and Public Policy Research.

Baker, T.G., 1983. Dry matter, nitrogen, and phosphorus content of litterfall and branchfall in Pinus radiata and Eucalyptus forests. N. Z. J. For. Sci. 13, 205–221.

Beets, P.N., Gielen, G., Oliver, G.R., Pearce, S.H., Graham, J.D., 2013. Determination of the Level of Soil N and P Storage and Soil Health at the Rotorua Land Treatment Site. New Zealand Forest Research Institute Limited.

Beukes, P.C., Gregorini, P., Romera, A.J., 2011. Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. Anim. Feed Sci. Technol. 166–167, 708–720. https://doi.org/10.1016/j.anifeedsci.2011.04.050.

Beukes, P.C., Depree, C., Macintosh, K.A., Silva-Villacorta, D., 2024. Stacking nitrogen mitigation strategies for future pasture-based dairy farms: impacts on leaching and profit. Frontiers in Animal Science 5, 1–8. https://doi.org/10.3389/fanim.2024.1277131.

Blakemore, L.C., Searle, P.L., Daly, B.K., 1987. Methods for chemical analysis of soils. https://doi.org/10.7931/DL1-SBSR-80.

Brandle, J.R., Hodges, L., Zhou, X.H., 2004. Windbreaks in North American Agricultural Systems. DigitalCommons @ University of Nebraska -, Lincoln.

Caradus, J.R., Goldson, S.L., Moot, D.J., Rowarth, J.S., Stewart, A.V., 2023. Pastoral agriculture, a significant driver of New Zealand's economy, based on an introduced grassland ecology and technological advances. J. Roy. Soc. N. Z. 53, 259–303. https://doi.org/10.1080/03036758.2021.2008985.

Cardozo Junior, F.M., Carneiro, R.F.V., Rocha, S.M.B., Nunes, L.A.P.L., dos Santos, V.M., de Lima Feitoza, L., de Araújo, A.S.F., 2018. The impact of pasture systems on soil microbial biomass and community-level physiological profiles. Land Degrad. Dev. 29, 284–291. https://doi.org/10.1002/ldr.2565.

Land use and altitude: how do they influence the phosphorus fractions? In: Carolyna, A., Ferreira, F., Andrade, F.V., Mendonça, E.D.S. (Eds.), Acta Scientiarum Agronomy 44, 1–9. https://doi.org/10.4025/actasciagron.v44i1.54801.

Chen, X., Condron, L.M., Dunfield, K.E., Wakelin, S.A., Chen, L., 2021. Impact of grassland afforestation with contrasting tree species on soil phosphorus fractions and alkaline phosphatase gene communities. Soil Biol. Biochem. 159, 108274. https://doi.org/10.1016/j.soilbio.2021.108274.

Cochrane, T.A., Zawar-reza, P., Bellamy, L., 2022. Resilient, Sustainable, and Profitable Agriculture in Canterbury.

Dai, Z., Liu, G., Chen, H., Chen, C., Wang, J., Ai, S., Wei, D., Li, D., Ma, B., Tang, C., Brookes, P.C., Xu, J., 2020. Long-term nutrient inputs shift soil microbial functional profiles of phosphorus cycling in diverse agroecosystems. ISME J. 14, 757–770. https://doi.org/10.1038/s41396-019-0567-9.

Dairy NZ, 2023. New Zealand Dairy Statistics 2022-23.

Dennis da Silva Ferreira, D., da Silva Rodrigues, L., de Carvalho Pereira-Filho, E.R., Manhães, F.M.V., Hilário, F.F., Castro, J.P., 2023. Principal component analysis for evaluation of chemical data. Quim. Nova 46, 747–754. https://doi.org/10.21577/0100-4042.20230030.

Dhillon, G.S., Van Rees, K.C.J., 2016. Soil organic carbon sequestration by shelterbelt agroforestry systems in saskatchewan. Can. J. Soil Sci. 97, 394–409. https://doi.org/10.1139/cjss-2016-0094.

Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutrient Cycl. Agroecosyst. 64, 237–256. https://doi.org/10.1023/A:1021471531188.

Diana, M., Araújo, M., Souza, H.A., Deon, D.S., Muniz, L.C., Costa, J.B., Souza, I.M., Roberto, V., Reis, R., Pereira, E., Franco, F., 2022. Integrated production systems in a Plinthosol: greenhouse gas emissions and soil quality. Aust. J. Crop Sci. 16, 184–191. https://doi.org/10.21475/ajcs.22.16.02.3263.

Dronen, S.I., 1988. Layout and design criteria for livestock windbreaks. Agric. Ecosyst. Environ. 22-23, 231–240. https://doi.org/10.1016/0167-8809(88)90020-5.

Fenton, T., 2012. Assessing environmental compliance of ponding and seepage from dairy feed pads and stand-off areas. Technical Report Waikato Regional Council.

Fernandez, M.A., Daigneault, A., 2017. Erosion mitigation in the Waikato district, New Zealand: economic implications for agriculture. Agric. Econ. 48, 341–361. https://doi.org/10.1111/agec.12338.

Gray, C.W., Ghimire, C.P., McDowell, R.W., Muirhead, R.W., 2021. The impact of cattle grazing and treading on soil properties and the transport of phosphorus, sediment and E. coli in surface runoff from grazed pasture. N. Z. J. Agric. Res. 65, 445–462. https://doi.org/10.1080/00288233.2021.1910319.

Gregory, N.G., 1995. The role of shelterbelts in protecting livestock: a review. N. Z. J. Agric. Res. 38, 423–450. https://doi.org/10.1080/00288233.1995.9513146.

Hawke, M.F., Dodd, M.B., 2003. Using trees on farms livestock shelter from trees- a review. Proc. N. Z. Grassl. Assoc. 65, 65–72.

Hawke, M.F., Knowles, R., 1997. Temperate agroforestry systems in New Zealand. In: Gordon, A.M., Newman, S.M. (Eds.), Temperate Agroforestry Systems. CAB International, London, pp. 85–118.

Hawke, M.F., Gillingham, A.G., Gray, M., Dean, M., 1999. The impact of shelterbelts in North Island East Coast dryland regions. Proc. N. Z. Grassl. Assoc. 195, 189–195. https://doi.org/10.33584/jnzg.1999.61.2342.

Hewitt, A.E., Balks, M.R., Lowe, D.J., 2021. The soils of Aotearoa New Zealand. World Soils Book Series. Springer.

Hoogendoorn, C.J., Betteridge, K., Ledgard, S.F., Costall, D.A., Park, Z.A., Theobald, P. W., 2011. Nitrogen leaching from sheep-, cattle- and deer-grazed pastures in the Lake Taupo catchment in New Zealand. Anim. Prod. Sci. 51, 416–425. https://doi.org/10.1071/AN10179.

Houlbrooke, D.J., Paton, R.J., Littlejohn, R.P., Morton, J.D., 2011. Land-use intensification in New Zealand: effects on soil properties and pasture production. J. Agric. Sci. 149, 337–349. https://doi.org/10.1017/S0021859610000821.

Jeyakumar, P., Loganathan, P., Anderson, C.W.N., Sivakumaran, S., McLaren, R.G., 2014. Comparative tolerance of Pinus radiata and microbial activity to copper and zinc in a soil treated with metal-amended biosolids. Environ. Sci. Pollut. Control Ser. 21, 3254–3263. https://doi.org/10.1007/s11356-013-2271-z.

Jin, D., Zhao, S., Zheng, N., Beckers, Y., Wang, J., 2018. Urea metabolism and regulation by rumen bacterial urease in ruminants - a review. Ann. Anim. Sci. 18, 303–318. https://doi.org/10.1515/aoas-2017-0028.

Kort, J., 1988. Benefits of windbreaks to field and forage crops. Agric. Ecosyst. Environ. 22–23, 165–190.

Lemanowicz, J., 2018. Dynamics of phosphorus content and the activity of phosphatase in forest soil in the sustained nitrogen compounds emissions zone. Environ. Sci. Pollut. Control Ser. 25, 33773–33782. https://doi.org/10.1007/s11356-018-3348-5.

Liu, J., Ding, C., Zhang, W., Wei, Y., Zhou, Y., Zhu, W., 2022. Litter mixing promoted decomposition rate through increasing diversities of phyllosphere microbial communities. Front. Microbiol. 13, 1–15. https://doi.org/10.3389/fmicb.2022.1009091.

McAdam, J., Short, I., Hoppé, G., 2006. Opportunities for silvopastoral systems in Ireland. The intersection of ecosystems, economics and society. Proceedings of IUFRO 3.08 Conference, Galway, Ireland, pp. 276–281.

Mize, C.W., Brandle, J.R., 2008. Ecological development and function of shelterbelts in temperate North America. U.S. Department Agriculture., For. Serv.–Natl. Agroforestry Centre, Lincoln, NE, pp. 27–53. https://digitalcommons.unl.edu/usdafsfacpub/.

Mize, C.W., Brandle, J.R., Schoeneberger, M.M., Bentrup, G., 2008. Ecological development and function of shelterbelts in temperate North America. U.S. Department Agriculture., For. Serv.–Natl. *Agroforestry Centre*, *Lincoln*, NE, pp. 27–54. https://doi.org/10.1007/978-1-4020-6572-9_3.

Mudge, P.L., Glover-Clark, G.L., McNeill, S.J.E., Dewhurst, Z., Penny, V., Rau, J., McKay, E., Hedley, C.B., Eger, A., Fraser, S., Foster, N., Roudier, P., McNally, S.R., Korth, M., Koele, N., Dooley, S., Reifschneider, L.E., O'Brien, L., Ward, A., Schipper, L.A., 2025. Design and results from a national soil carbon stock benchmarking and monitoring system for agricultural land in New Zealand. Geoderma 459. https://doi.org/10.1016/j.geoderma.2025.117354.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Nguyen, T.B.A., Henao, L.A., Li, Z., Cheng, L., Hu, H.W., 2023. Impacts of shelterbelt systems on pasture production and soil bacterial and fungal communities in agricultural fields. J. Sustain. Agric. Environ. 2, 301–313. https://doi.org/10.1002/sae2.12059.

Omaliko, C.P.E., 1981. Dung deposition, breakdown and grazing behavior of beef cattle at two seasons in a tropical grassland ecosystem. J. Range Manag. 34, 360. https://doi.org/10.2307/3897903.

Pardon, P., Reubens, B., Reheul, D., Mertens, J., Frenne, P.D., Coussement, T., Janssens, P., 2017. Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems. Agric. Ecosyst. Environ. 247, 98–111. https://doi.org/10.1016/j.agee.2017.06.018.

Parfitt, R.L., Ross, D.J., 2011. Long-term effects of afforestation with Pinus radiata on soil carbon, nitrogen, and pH: a case study. Soil Res. 49, 494–503. https://doi.org/10.1071/SR11106.

Pereira, R.C., Hedley, M.J., Arbestain, M.C., Bishop, P., Enongene, K.E., Olsson, I.J., 2018. Evidence for soil carbon enhancement through deeper mouldboard ploughing at pasture renovation on a typic fragiaqualf. Soil Res. 56, 182–191. https://doi.org/10.1071/SR17039.

Qiao, Y., Fan, J., Wang, Q., 2016. Effects of farmland shelterbelts on accumulation of soil nitrate in agro-ecosystems of an oasis in the Heihe River Basin, China. Agric. Ecosyst. Environ. 235, 182–192. https://doi.org/10.1016/j.agee.2016.10.021.

R Core Team, 2023. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rae, A., Strutt, A., Cassells, S., 2008. Towards analysis of sustainable export-oriented agriculture: exploring land-use data and CGE modelling in New Zealand. Agricultural Economics Research Unit Discussion Paper.

Rutigliano, F.A., Marzaioli, R., Grilli, E., Coppola, E., Castaldi, S., 2023. Microbial, physical and chemical indicators together reveal soil health changes related to land cover types in the southern European sites under desertification risk. Pedobiologia 99–100, 150894. https://doi.org/10.1016/j.pedobi.2023.150894.

Rys, G.J., Gibbs, J., Clark, D.A., Lambert, G., Clark, H., Newman, M., 2021. Productivity, changes and resilience in New Zealand grassland agriculture over the last three decades. Proc. N. Z. Grassl. Assoc. 83, 1–8.

Scholten, H., 1988. Snow distribution on crop fields. Agric. Ecosyst. Environ. 22–23, 363–380. https://doi.org/10.1016/0167-8809(88)90032-1.

Sigurdarson, J.J., Svane, S., Karring, H., 2018. The molecular processes of urea hydrolysis in relation to ammonia emissions from agriculture. Rev. Environ. Sci. Biotechnol. 17, 241–258. https://doi.org/10.1007/s11157-018-9466-1.
Soliman, T., Walsh, P., 2005. Valuing the effect of soil erosion on productivity. Environment 7, 1–14.
Subbarao, G.V., Sahrawat, K.L., Nakahara, K., Rao, I.M., Ishitani, M., Hash, C.T., Kishii, M., Bonnett, D.G., Berry, W.L., Lata, J.C., 2013. A paradigm shift towards low-nitrifying production systems: the role of biological nitrification inhibition (BNI). Ann. Bot. 112, 297–316. https://doi.org/10.1093/aob/mcs230.
Sun, Q., Zheng, B., Liu, T., Zhu, L., Hao, X., Han, Z., 2022. The optimal spacing interval between principal shelterbelts of the farm-shelter forest network. Environ. Sci. Pollut. Control Ser. 29, 12680–12693. https://doi.org/10.1007/s11356-021-17272-1.
Teo, H.C., Lamba, A., Ng, S.J.W., Nguyen, A.T., Dwiputra, A., Jia, A., Lim, Y., Nguyen, M. N., 2025. Reduction of deforestation by agroforestry in high carbon stock forests of Southeast Asia. Nat. Sustain. https://doi.org/10.1038/s41893-025-01532-w.
Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G., Plieninger, T., 2016. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric. Ecosyst. Environ. 230, 150–161. https://doi.org/10.1016/j.agee.2016.06.002.
Udawatta, R.P., Kremer, R.J., Adamson, B.W., Anderson, S.H., 2008. Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. Appl. Soil Ecol. 39, 153–160. https://doi.org/10.1016/j.apsoil.2007.12.002.
Vasylivna, V.O., Kravchenko, Y.S., Zhang, X., Song, C., Yarosh, A.V., 2021. Seasonal dynamics of microbial biomass carbon and nitrogen under different tillage systems. Preprints 2021120388. https://doi.org/10.20944/preprints202112.0388.v1.
Vogeler, I., Vibart, R., Cichota, R., 2017. Potential benefits of diverse pasture swards for sheep and beef farming. Agric. Syst. 154, 78–89. https://doi.org/10.1016/j.agsy.2017.03.015.
Wojewoda, D., 2003. The impact of a shelterbelt on soil properties and microbial activity in an adjacent crop field. Pol. J. Ecol. 51, 3–14.
Xin-Qi, W., Chuan-Kuan, W., Han, Yi., 2015. Tree-species effects on soil organic carbon density: a common garden experiment. Chin. J. Plant Ecol. 39, 1033–1043. https://doi.org/10.17521/cjpe.2015.0100.
Zhang, X., Hedēnec, P., Yue, K., Ni, X., Wei, X., Chen, Z., Yang, J., Wu, F., 2024. Global forest gaps reduce litterfall but increase litter carbon and phosphorus release. Commun. Earth Environ. 5, 1–10. https://doi.org/10.1038/s43247-024-01453-0.
Zhang, J., Jing, W., Ji, K., Zhang, Y., 2025. Soil characteristics and bacterial community characteristics of shelterbelts of different tree species in black soil region of China. Sci. Rep. 15, 1–13. https://doi.org/10.1038/s41598-025-92051-3.
Zheng, X., Zhu, J., Xing, Z., 2016. Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China. Agric. Syst. 143, 49–60. https://doi.org/10.1016/j.agsy.2015.12.008.
Zhou, J., Shao, G., Kumar, A., Shi, L., Kuzyakov, Y., Pausch, J., 2022. Carbon fluxes within tree-crop-grass agroforestry system: 13C field labeling and tracing. Biol. Fertil. Soils 58, 733–743. https://doi.org/10.1007/s00374-022-01659-4.
Zhu, M., Cheng, G., Zhang, X., Guo, Y., Wu, Y., Wang, Q., 2023. Shelterbelts increased soil inorganic carbon but decreased nitrate nitrogen, total phosphorus, and bulk density relative to neighbor farmlands depending on tree growth, geoclimate, and soil microbes in the Northeast China Plain. Catena 231, 107344. https://doi.org/10.1016/j.catena.2023.107344.