Impact of diverse pastures and reduced nitrogen inputs on dairy pasture yields, botanical composition and soil health across three regions

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Abstract

Pastoral farmers can enhance productivity and minimise environmental impacts by utilising a range of management practices on farm. Different pasture management options being explored for their potential benefit to the farm and wider ecosystem include the use of diverse pasture species and targeted fertiliser nitrogen (N) inputs. On each of nine dairy farms across Waikato, Canterbury and Otago, one paddock was sown with a pasture mix containing perennial ryegrass/white clover/plantain (simple) and an adjacent paddock sown with an additional 12 species (diverse). Half of each paddock received either standard or low N fertiliser inputs. Herbage yields were determined for three years, with pasture species composition assessed seasonally. Soil health was assessed annually using measures of soil fertility, organic matter, physical condition and biological abundance.

Total annual pasture yields were no different between the simple and diverse pastures. Pasture growth tended to be reduced in response to lower N fertiliser inputs, although results were not significant. The most consistent pasture responses to N were seen in Canterbury under irrigation. Under low N inputs there was a small increase in white clover (>1%), and although non-significant still created the potential for increased biological N_2 fixation. Plantain declined during the study from 20±2.7% to 2±0.8% in both pasture types. Grass contributed over half of the pasture sward. Although ryegrass was the dominant species in both pasture types, diversity remained higher within the diverse sward in the final year of study, with other grass species contributing up to 20±1.8% of the pasture sward. There was no effect of pasture type, N rate, or their interaction on any measured soil health property.

Keywords: forage production, multispecies pastures, persistence, soil condition

Introduction

Perennial pastures grazed by livestock throughout the year underpins New Zealand's pastoral agriculture systems. These pastures have traditionally been reliant on biological nitrogen (N) fixation from the atmosphere by rhizobia living symbiotically within nodules on the roots of legumes (Ledgard et al. 1996). However, even in well-managed legume-based pastures, N requirements are not necessarily met through biological N fixation alone (Steele 1982). In most situations the application of fertiliser N will give a positive herbage yield response (Gray 2023). Since 1990, there has been an increase in the use of N fertiliser within dairy pastures, moving from strategic use of N fertiliser to extend the growing season, to more frequent applications following grazing events to boost total production (Chapman et al. 2025).

Increasing the amount and reliability of pasture grown throughout the year increases milk yield via increased per cow performance or stocking rate (McGrath et al. 1998). However, associated with this intensification are increased risks to the environment. These include risk of soil structural degradation from increased treading pressures (Houlbrooke et al. 2011); losses of N to water bodies (Cameron et al. 2013), especially from excess soil N in urine patches (Selbie et al. 2015); and greenhouse gas emissions to the atmosphere via denitrification of excess soil N and biogenic methane from increased feed intake (Kankanamge et al. 2025). The challenge for dairy farm sustainability involves maintaining or increasing milk production while operating within management guidelines and regulations intended to limit environmental impacts.

New Zealand introduced a 190 kg N ha^{-1} cap on annual N fertiliser use on pastoral farms in 2021, aiming to reduce N leaching losses to receiving environments (Ministry for the Environment 2021). It is well recognised that symbiotic N_2 fixation rates are inversely proportional to fertiliser N input rates

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and legume yields (Ledgard et al. 1996; Burchill et al. 2014). Thus, reducing N inputs beyond the current regulated limits may not constrain productivity, as a result of compensatory increases in associated biological N_2 fixation rates (Ledgard et al. 2001; Gray 2023), assuming an adequate amount of legume can be maintained in the pasture.

Changes in pasture type and botanical composition are other options to maintain current productivity while minimising environmental impacts. For example, including plantain (*Plantago lanceolata*) within traditional perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) swards has been shown to be an effective way to reduce N losses from the system without impacting productivity (Pinxterhuis et al. 2024; Dodd et al. 2025). Despite challenges in maintaining plantain at levels sufficient to offer functional benefits within the pasture sward (Dodd et al. 2022), plantain offers a practical on-farm pasture management solution. Sowing 'hyper' diverse pastures mixes, containing upwards of 15 species, advocated under regenerative management principles may also offer another option (Tozer et al. 2023). It has been suggested however, that the presence of key functional species may be more important than the number of species (Vibart et al. 2016).

One of the often-stated goals of regenerative management is the improvement of soil health (Khangura et al. 2023) which may provide protection from soil degradation , however results vary with soil, climate and land use (Hawes et al. 2025; Arp et al. 2026). Such initiatives must be considered in the context of well-established and effective New Zealand pastoral management practices (Rowarth et al. 2020). The objective of this study was to investigate the impact of increasing sown pasture species diversity and reducing N fertiliser inputs on pasture production, botanical composition and the flow-on effects on soil health across nine dairy farms located in three regions of New Zealand.

Materials and Methods

The experiment monitored pastures on nine dairy farms located across the Waikato, Canterbury and Otago regions (Table 1). Weather data was collected from nearby weather stations (ECan; ESNZ), with rainfall data recorded within 10 km of each farm and air temperature within 30 km. Average annual rainfall during the study period was highest on the Waikato farms (1362 mm), in comparison to Canterbury (767 mm) and Otago farms (687 mm, Figure 1). Only the Canterbury farms were irrigated from September to April. Trial paddocks in Waikato were located on Allophanic soils, in Canterbury farms were split evenly between Brown soils and Gley soils while in Otago

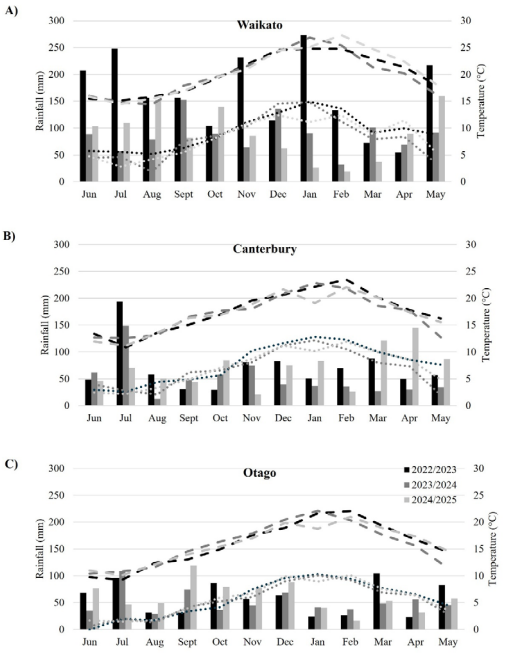


Figure 1 Average monthly rainfall (bars) and maximum (dashed line) and minimum (dotted line) air temperature in A) Waikato, B) Canterbury and C) Otago determined from nearby weather stations (ECan ; ESNZ).

trial paddocks were located on Pallic soils (S-Map). The trial paddocks were selected based on similar management history for >5 years. In Waikato and Canterbury neighbouring paddocks were established following a permanent pasture, in Otago paddocks were subdivided following a fodderbeet crop. Paired paddocks were determined to have similar soil loss risk (Donovan 2022).

Prior to trial establishment soil health was assessed using a combination of laboratory and field measures. Indicators of soil fertility, organic matter properties, physical condition and biological activity were assessed in relation to associated target ranges described in Schon and Mackay (2023). Briefly, soil cores (20 cores of 25 mm diameter, 0–75 mm depth) were bulked and sent to a commercial laboratory (Hill Labs) for analysis of soil pH (1:2.5 soil:water), Olsen P (Olsen et al. 1954), potassium (K), calcium (Ca), magnesium (Mg), sulphate sulphur (S), organic S, hot water extractable carbon (HWEC, Ghani et al. 2003), anaerobically mineralisable N (AMN, Keeney and Bremner 1966), total soil organic carbon (C) and total soil N (Dumas combustion, Bremner 1996). At the start, middle and end of each transect a Visual Soil Assessment (VSA) was conducted to assess soil physical health (Shepherd 2000). The VSA scores also include an assessment of earthworm abundance by hand-sorting a 200 mm ×

Table 1 Number of farms in each region, with average size of farms and trial area sown. Details on pasture establishment, N fertiliser inputs (kg N ha^{-1} y^{-1}) and average annual pasture yields (kg DM ha^{-1}) are also given.

	Waikato	Canterbury	Otago
Number of dairy farms	2	4	3
Average farm size (ha)	133	319	260
Irrigation	No	Yes	No
Wintering	On-farm	Off-farm	Off-farm
Average area sown (ha)	1.7	6.0	2.0
Soil order	Allophanic	Brown/Gley	Pallic
Crop prior	Pasture	Pasture	Fodder beet
Cultivation	Surface	Plough	Plough
Sown	March 2022	December 2021/ January 2022	September 2022
Low N application (kg N ha^{-1} y^{-1})	30	60	60
Standard N application (kg N ha^{-1} y^{-1})	90	180	150
Annual pasture yields (kg DM ha^{-1})			
2022/2023[1]	22 640	22 305	
2023/2024	19 220	19 855	18 000
2024/2025	16 640	17 964	16 940

[1] Otago pastures were sown in spring 2022 and total annual yield was not determined.

200 mm × 200 mm soil sample. Earthworm biomass was also determined and species diversity recorded. Earthworm species in ecological groups included epigeic *Lumbricus rubellus*, endogeic *Aporrectodea caliginosa* and anecic *Aporrectodea longa*. Insect pasture pests were identified, including porina (*Wiseana* sp.), grass grub (*Costelytra zealandica*), clover root weevil (*Sitona lepidus*) and black beetle (*Heteronychus arator*). For each soil health indicator, distance from target range was calculated as described by (Schon and Roberts 2020). Soil health indicator values at or within their optimal range were given a score of 1, while a score less than 1 indicated soil health to be either above or below target. Soil health status between paired paddocks were determined to be similar prior to establishment. Soil health assessments were repeated annually in winter. Soil total mineral N in the topsoil was determined at the time of annual sampling in 2025 using a KCL extraction (Blakemore et al. 1987).

On each farm a 'simple' three-species pasture of perennial ryegrass (*L. perenne*), white clover (*T. repens*) and plantain (*P. lanceolata*) was sown in one paddock at a rate of 28.5 kg seed ha^{-1}, and in an adjacent paddock on the same soil type, a 'diverse' 15 species pasture was sown at 39.5 kg seed ha^{-1} (Table 2). The simple pasture was the standard pasture in current use on the farms monitored. Pastures were sown in Canterbury in December 2021/January 2022, in Waikato in March 2022 and in Otago in September 2022 (Table 1). Individual applications of 30 kg N ha^{-1} as solid urea (46% N) were applied, with half of each paddock receiving a 'standard' N fertiliser rate of 90–180 kg N ha^{-1} y^{-1}, based on regional averages as provided by the dairy processors, or reducing to a 'low' N fertiliser rate of 30–60 kg N ha^{-1} y^{-1}. Under low N, urea was applied only in spring (30 kg N ha^{-1}), or in both spring and autumn (60 kg N ha^{-1}). Pastures were rotationally grazed by dairy cows. Rotation length was the same for both pasture types (target 22-32 days), with the simple and diverse pastures being grazed consecutively, and N treatments grazed simultaneously. Target post-graze residuals of simple pastures were 1600 kg dry matter (DM) ha^{-1}. The targeted post-graze residuals in the diverse pastures were 400 kg DM ha^{-1} higher but averaged only 100 kg DM ha^{-1} higher than the simple pastures.

Pasture cages were used to assess herbage DM accumulation and estimate monthly and annual pasture yields for three years following establishment (first year 2022/2023, second year 2023/2024 and third year 2024/2025). Pasture cages were placed in representative sites (three per treatment). After each grazing, the standing herbage within pasture cages was assessed within a 0.5 m^2 quadrat by trimming the herbage to ground level. Immediately adjacent to each of the pasture cages, representative post-graze residuals were also determined by trimming herbage within a 0.5 m^2 quadrat to ground level. After each grazing the pasture cage was moved to a new representative position within the treatment area. Harvested herbage was washed

Table 2 Pasture species and sowing rate (kg ha^{-1}) for the simple and diverse swards.

Species	Cultivar	Sowing Rate (kg ha^{-1})	
		Simple	Diverse
Perennial ryegrass (*Lolium perenne*) - diploid	One50 + AR37	13.5	4.5
- tetraploid	Base + AR37	9	3
Hybrid ryegrass (*Lolium hybridum*)	Mohaka + AR37		2
Tall fescue (*Lolium arundinaceum*)	Hummer + MaxP		4
Meadow fescue (*Lolium pratense*)	Oakdon + MaxR		4
Timothy (*Phleum pratense*)			1
Prairie grass (*Bromus willdenowii*)*	Atom		4
White clover (*Trifolium repens*)	Attribute	2	2
	Brace	2	2
Red clover (*Trifolium pratense*)	Relish		3
Crimson clover (*Trifolium incarnatum*)			1
Persian clover (*Trifolium resupinatum*)	Resal		1
Balansa clover (*Trifolium balansae*)	Viper		1
Lucerne (*Medicago sativa*)	Titan5		2
Vetch (*Vicia sativa*)			2
Plantain (*Plantago lanceolata*)	Ecotain	2	
Chicory (*Cichorium intybus*)	Choice	2	1
Total		28.5	39.5

* Swapped for cocksfoot (*Dactylis glomerata*) cv. Savvy on one farm.

separately to remove extraneous matter and dried (at 95°C for 48 hours) to determine total DM. Each mid-season, a sub-sample of approximately 400 pieces was collected from the harvested herbage to identify pasture species and dead matter. Additionally, bulked subsamples were collected for chemical analysis. Herbage was dried at 50ºC and sent to a commercial laboratory (Hill Labs) for analysis of feed quality profile, including crude protein, N and metabolizable energy (ME). Nitrogen fixation was calculated using legume DM (kg ha^{-1}), N% (4%) and assumed N derived from symbiosis based on calculations described in Lucas et al. (2010). The pasture growth response to N was calculated by determining the difference in pasture DM in relation to the extra N applied. Additional N inputs from legumes and livestock grazing were not accounted for in the calculation.

Statistical analyses were conducted in R (version 4.3.3; R Core Team 2024) to assess treatment effects on pasture yields, composition and soil health properties. Linear models were fitted with pasture type, N rate, and their interaction as fixed effects, using either the original response variable or a log transformed version (log(Y + 0.1)) where non-constant residual variance was observed, depending on the specified model type. Analysis of variance was used to assess differences prior to treatments being established and the significance of the N and pasture type × N rate interaction. Pairwise comparisons ("Predictmeans" package using Tukey alpha level 0.05) were conducted using least significant difference. Region was not included as a fixed effect in the statistical models as replicates were not balanced across regions, but figures in the results section present regional differences. Treatment means were calculated for each pasture type × N rate combination and raw data presented in results section. Standard errors of the difference between means (SED) are reported. There were few significant differences and p-values are only shown when significant ($p<0.05$).

Pasture growth was assessed using Flexi 12.10 (Upsdell 1996). This approach models lagged relationships between sampling periods and allows for smooth representations of temporal patterns. The model specification initially included pasture type, N fertiliser rate, region, a cyclic seasonal trend, and time. This smoothing framework produces fitted curves for both explained and unexplained variation and does not rely directly on degrees of freedom in the same way as linear models. Model comparison using Akaike Information Criterion indicated that smooth models including Region did not improve the explanation of variation relative to models excluding Region (supporting the exclusion of Region from the linear models).

Table 3 Average annual pasture yields (kg DM ha^{-1}) and N response (kg DM kg^{-1} N) for the two pasture types and two N fertiliser rates across three regions. Standard errors of difference (SED) given, with no significant treatment differences observed.

Milking season	Pasture yield (kg DM ha^{-1})				SED	N response[1] (kg DM kg^{-1} N)
	Simple		Diverse			
	Low N	Standard N	Low N	Standard N		
2022/2023[2]	21 790	23 010	21 760	23 100	2 075	17
2023/2024[3]	17 220	19 585	18 455	19 125	1 630	15
2024/2025	17 840	18 380	16 485	16 605	2 020	3

[1] Relative response of the standard N treatment when compared with the low N treatment.
[2] Only Waikato and Canterbury data as Otago pastures were sown in spring 2022 and total annual yield was not determined.
[3] The simple pasture on one Waikato farm had reduced yields in 2023/2024 due to ongoing weed management and pasture yield were excluded here.

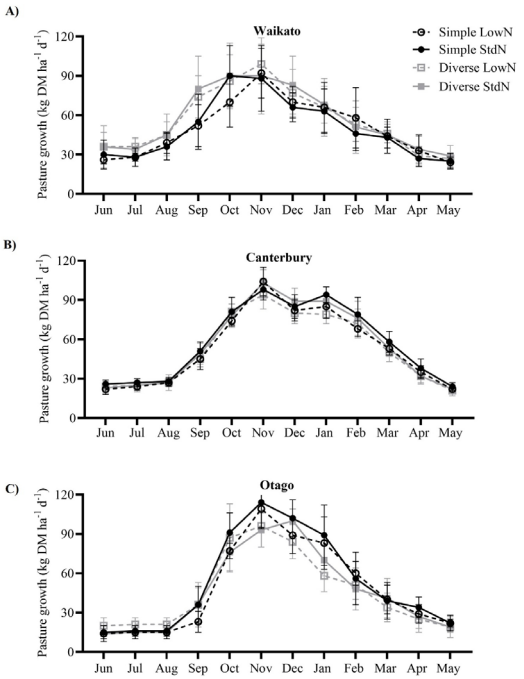


Figure 2 Average monthly pasture growth rates (across all study years) for the two pasture types and two N fertiliser rate combinations calculated from all farms within each region A) Waikato, B) Canterbury and C) Otago. Error bars are standard error of mean.

Results

Pasture yield

Annual pasture yields were highest in the first year of the study and were not different between the simple and diverse pasture mixes (22 400 vs. 22 430±2075 kg DM ha^{-1}, respectively, Table 3). In 2023/2024 pasture yield remained similar between the two pasture types. Although not significant, there was an indication that pasture yield was lower in the diverse pasture in the third year (18 110 vs. 16 545±2020 kg DM ha^{-1}, respectively). These apparent lower yields in 2024/2025 were seen primarily in Otago, where yields reduced by an average of 3000 kg DM ha^{-1} in the diverse in comparison to the simple pastures. Average annual yields observed in each region are presented in Table 1.

Reducing N applications tended to reduce pasture growth by an average 1200 kg DM ha^{-1} across the two pasture types in the first two years of the study, but this was not significant both in terms of monthly (Figure 2) or annual growth rates (Table 3). The largest relative response to N fertiliser inputs was observed in the first two years of the study, with average response rates being >15 kg DM kg^{-1} N across all regions (Table 3), although this did not account for additional N inputs from legumes and livestock grazing. In the final year of the study there was no difference in pasture yields between the two N treatments in Waikato and Otago. In Canterbury, under irrigation, average pasture response to N inputs across both pasture types had reduced to 9 kg DM kg^{-1} N.

Botanical composition

Following establishment, white clover content initially tended to be higher in the simple pasture than in the diverse pasture (12.0 vs. 8.8±2.6% respectively, Figure 3). Other legumes that were part of the diverse pasture sowing mix (Table 2) were higher in the diverse than in the simple pasture during the first year ($P<0.05$, 5.9 vs. 1.0±0.97%), despite a small percentage of red clover also detected in the simple pasture. By the second year (2023/2024), the contribution of the annual clovers, red clover, lucerne and vetch sown in the diverse pasture mix had declined to less than 2.5±0.38% of the pasture sward (Figure 3). Lucerne and vetch contributed little to the total sward across the regions and years, and by the final year contributed <0.1%. By the final year (2024/2025) white clover had reduced on average to 10.2±3.1%, with peak content observed in summer (15.6±6.1%). White clover content in Canterbury was

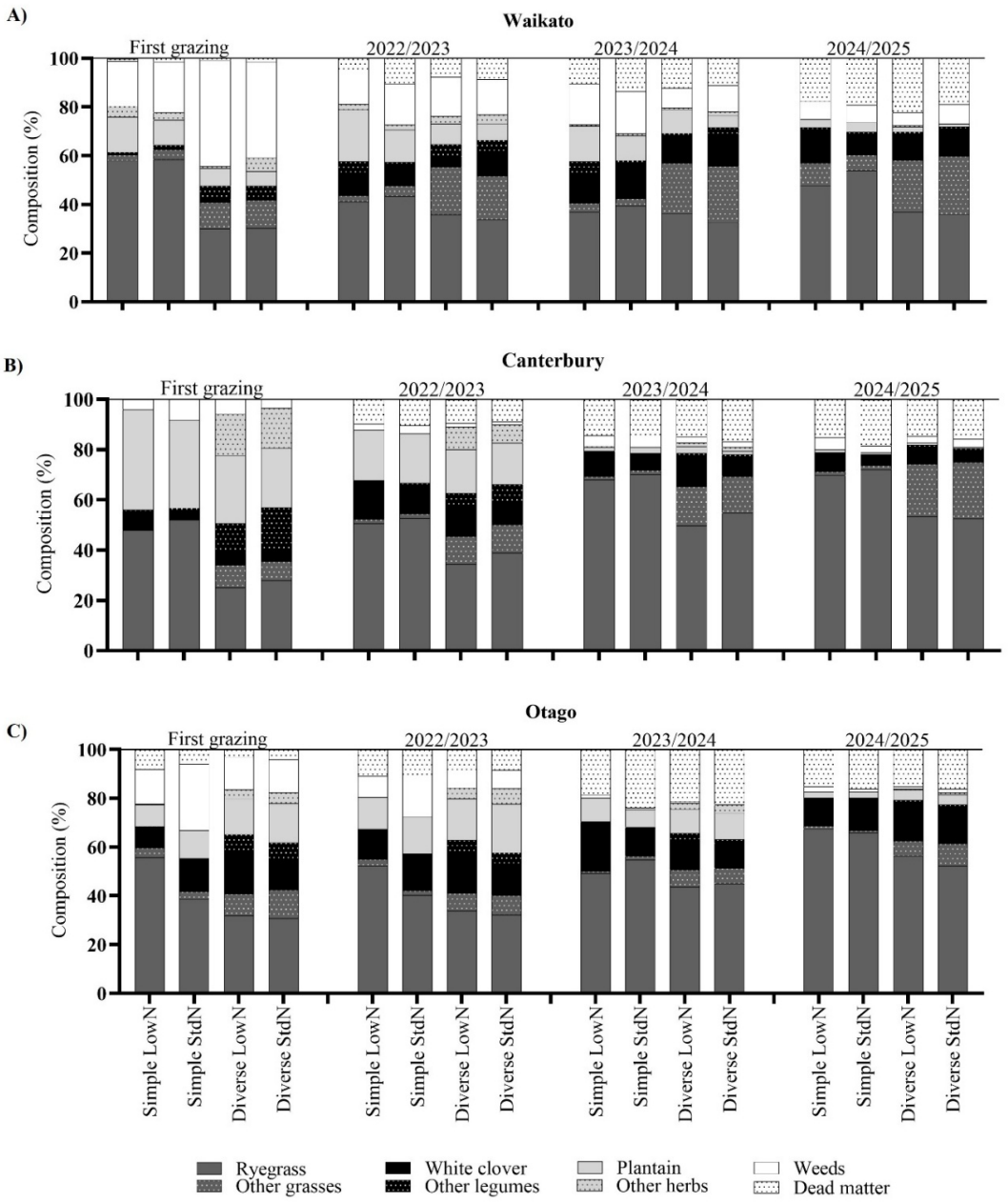


Figure 3 Pasture botanical composition (% of harvested DM) measured at the first harvest and then averaged over four seasonal harvests within each milking season, for the two pasture types and two N fertiliser rate combinations on study farms in A) Waikato, B) Canterbury and C) Otago (Otago data in 2022/2023 only from summer and autumn). In 2024/2025 the composition of other grasses in Waikato was 11±1% fescue, 0.4±0.7% timothy and 7.6±1.5% prairie grass; in Canterbury was 9.5±1% fescue, 4.8±0.7% timothy and 3.2±1.5% prairie grass; and in Otago was 2.1±1% fescue, 1.3±0.7% timothy and 3.3±1.5% prairie grass.

6.0±3.1% in the sward in comparison to 11.0±3.1% in Waikato and 13.9±3.1% in Otago. There were no significant treatment effects on white clover contents, although white clover tended to be greater in the low than standard N treatments 10.5 vs. 9.0±3.1%. By the final year (2024/2025) N fixation by legumes was calculated to be 28 kg N ha^{-1} y^{-1} in the standard N treatment by legumes compared with 49 kg N ha^{-1} y^{-1} in the low N treatment.

Throughout the three years the percentage of total

Table 4 Average pasture composition (%) by individual species for the two pasture types and two N fertiliser rates across the three regions in the final year of study (2024/2025). Standard errors of difference (SED) given, with no significant treatment differences observed.

Pasture species	Pasture composition (%)				SED
	Simple		Diverse		
	Low N	Standard N	Low N	Standard N	
Ryegrass	64	66	51	49	7
Fescue (tall and meadow)	0	0	7	8	1
Timothy	0	0	2	3	0.7
Prairie grass*	0	0	5	6	1.5
White clover	10	8	11	10	4
Red clover	0	0	0.5	0.7	0.3
Lucerne	0	0	0	0	0.1
Vetch	0	0	0	0	0
Chicory	0	0	0	0	0.1
Plantain	2	2	2	2	0.8
Weeds/unsown	8	6	4	4	1.5
Dead matter	16	18	17	17	2

*Cocksfoot on one farm

sown grass was similar across both pasture types (Figure 3). Grass contributed close to half of the pasture sward in the first year (2022/2023). Perennial ryegrass was the dominant grass species in both pasture types, although in the diverse pasture, tall fescue, timothy and prairie grass contributed 11.3±2.4% in total to the pasture sward. By the third year (2024/2025) grass contributed over half of the pasture sward, with grass content highest in Canterbury, then Otago, with the lowest grass content in the sward observed in Waikato. In the final year 20±1.8% of the diverse pasture sward in Waikato and Canterbury were grasses other than perennial ryegrass, but only 7±1.8% other grasses were observed in Otago. Of the other grasses, fescue and prairie grass contributed the most to the pasture sward in Waikato in 2024/2025, with timothy contributing <1±0.7% to the total sward (Table 4). In Canterbury, fescue was close to 10±1.0% of the sward, while timothy and prairie grass were <5 % of the sward. In Otago, prairie grass was the most common other grass, although the contribution was <3±1.5% to the total sward.

Plantain established well in both pasture types, contributing about 20±2.7% of total dry matter to the pasture sward at the time of the first grazing (Figure 3). However, by the third year of study (2024/2025) plantain contributed 3% of the sward in Waikato and Canterbury, but only 1% in Canterbury (Table 4).

The percentage of weeds and unsown species remained high (>10±1.5%) in Waikato in the third year (2024/2025), despite ongoing control of broad-leaved dock on one Waikato farm. The Waikato pastures were sown in a dry autumn, with weed burden at the first grazing up to 40±2.5% of the total DM (Figure 3). Both pasture types were sprayed for weeds in spring. The simple pasture required further weed management the following spring, resulting in lower pasture yields (Figure 2). By the third year, there were no differences in pasture yield between the two pasture types.

Soil properties

Baseline measurements of soil nutrient fertility, organic matter concentration, physical condition and biological abundance showed no significant differences across treatments prior to the establishment of the study. While the majority of soil health indicators were at or close to target, Mg, organic S, earthworm abundance and diversity were typically not at target (Figure 4). In Otago, soil physical condition using VSA scores were not at target, as a result of a winter fodderbeet crop grown prior to establishment to trial establishment. In the year following pasture establishment there was a measured decline in some soil health indicators in Canterbury, with declines in Olsen P, total soil organic C and N following cultivation and pasture renewal. In Otago there was a measured improvement in soil physical condition which remained three years after the treatments were established, with earthworm abundance also improved to target levels. On the Canterbury farms total soil organic C at 0-7.5 cm depth remained below pre-establishment levels in winter 2025 (4.8±0.1% vs. 4.1±0.1%). However, there were no significant treatment differences in any of the soil health indicators (Table 5). Topsoil mineral N levels at the study sites in

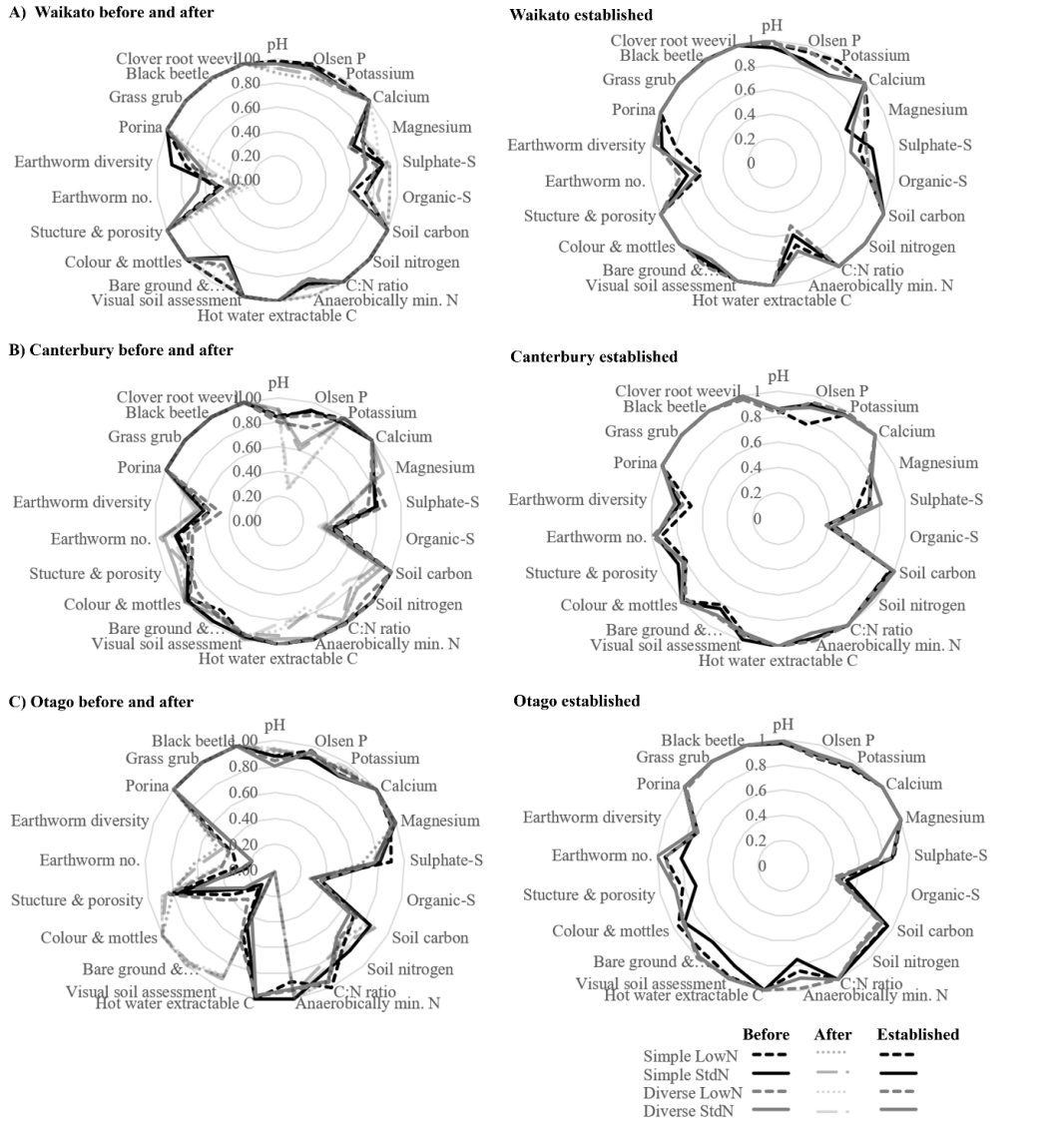


Figure 4 Average soil health scores shown as standardised distances from target ranges in the winter before and after pasture establishment, and once pastures were well established in 2025 on study farms in A) Waikato, B) Canterbury and C) Otago. The optimal range is represented by 1.0. Indicators not at 1.0 may be either above or below their target range.

winter 2025 were not different between the treatments and were on average 32.4±4.1 mg kg^{-1} in Waikato, 7.9±4.1 mg kg^{-1} in Canterbury and 13.9±4.1 mg kg^{-1} in Otago.

Discussion

Following pasture renewal, pasture yields were similar between the simple and diverse pastures (Table 3). These results align with a comparison between a diverse and conventional sward in Manawatū which found no significant differences in the first year following sowing (Sutharsan et al. 2025). Some regional differences were recorded. For example, during the final year of the current study pasture yields of all treatments were similar in Waikato and Canterbury, but lower in the diverse than simple pasture in Otago following a wet spring.

Reductions in N fertiliser inputs reduced average yields by approximately 1200 kg DM ha^{-1} in the first 2 years of the study, although this was not significant (Table 3). After accounting for differences in fertiliser N inputs across the nine farms, the pasture response to extra nitrogen inputs in the first two years of the study averaged >15 kg DM kg^{-1} N. This aligns closely with

Table 5 Average soil properties across all farms shown for the two pasture types and two N fertiliser rate combinations in winter 2025. Standard errors of difference (SED) given, with no significant treatment differences observed.

	Simple		Diverse		SED
	Low N	Standard N	Low N	Standard N	
Soil pH	6.1	6.2	6.1	6.1	0.1
Olsen P (μg ml^{-1})	33	38	34	37	7
Potassium (MAF QT)	11	13	11	13	2
Calcium (MAF QT)	11	11	11	11	2
Magnesium (MAF QT)	35	37	35	36	7
Sulphate-sulphur (mg kg^{-1})	15	13	15	18	4
Organic-sulphur (mg kg^{-1})	8	8	8	8	1
Soil C (%)	5.3	5.4	5.3	5.2	1.2
Soil N (%)	0.50	0.52	0.51	0.50	0.1
Soil C:N ratio	10.7	10.6	10.6	10.5	0.3
Anaerobically min. N (μg g^{-1})	229	225	191	230	25
Hot water extractable C	2285	2440	2278	2246	190
Visual soil assessment score	21	21	21	21	1
Bare soil and surface relief score	4	4	4	4	1
Colour and mottles score	7	7	7	7	1
Structure and porosity score	8	8	8	9	1
Earthworm abundance (m^{-2})	536	505	524	486	94
Earthworm ecological groups (#)	2	2	2	2	0.2
Porina (m^{-2})	2	2	6	3	0.5
Grass grub (m^{-2})	17	15	26	35	7
Black beetle (m^{-2})	1	1	2	4	0.2
Clover root weevil (m^{-2})	69	57	70	39	23

observations of average responses across New Zealand pasture studies (Gray 2023). In the final year there was no material response to N application in Waikato and Otago. However, an N response was observed on farms located in Canterbury across all years, although the N response rates were also negligible in the diverse pasture in the final year. It is not clear why there were differences between the two pasture types, but this may in part be due to other pasture species in the diverse sward being less responsive to N inputs (Cowling and Lockyer 1965). Overall the more predictable pasture response to N in Canterbury was likely the result of a combination of factors, including irrigation removing limitations to plant growth (Black and Murdoch 2013), lower incidence of soil disease (Dignam et al. 2022), as well as lower topsoil mineral N levels at the study sites impacting the pastures ability to respond to N inputs. Gray (2023) also reported the highest N use efficiency rates in Canterbury soils compared with other regions.

The average legume content throughout the first year of study tended to be lower in the in the simple than in the diverse sward, with white clover dominating, but other legumes still contributing 5.9±0.97% to the diverse sward. By the final year (2024/2025) total legume content had reduced on average to approximately 10% of the sward, continuing to be dominated by white clover, with other legumes contributing <1% (Table 4). Although the legume content of swards was similar across regions in the first year after sowing, by the final year pastures in Canterbury had a lower percentage of white clover in the sward, in comparison to Waikato and Otago, reducing the potential for biological N fixation. White clover content and yield declines when N fertiliser is applied (Crush et al. 1982; Ledgard et al. 1987; Gray 2023), and the lower legume content on the farms in Canterbury might reflect the fact that these farms received the highest rates of fertiliser N inputs.

Overall legume content was low, constraining biological N fixation from the atmosphere (Chapman et al. 1996). In addition to reducing clover content in the sward, N application further diminishes the ability of clover to fix atmospheric N by reducing nodule formation, as well as preferential uptake of soil mineral N by clover (Gray 2023). Even when N availability in

the soil is high, 15% of total uptake of N in white clover is via biological N fixation (Chapman et al. 1996). Through a combination of lower legume content under standard N and reduced N fixation when N fertiliser is applied (Lucas et al. 2010), it was calculated that N fixation was 20 kg N ha^{-1} y^{-1} greater under the low N treatment than in the standard N treatment across all years of the study. The additional N fixation under low N highlights the value of legumes within our pasture systems (Walker 1996).

Plantain, a short-lived perennial herb, established well across all sites and treatments, contributing about 20±2.7% of total dry matter to the pasture sward at the time of the first grazing. However, within 3 years, plantain content had reduced to on average 2±0.8% of the pasture sward in all regions, but <1% in Canterbury. Although it has been well documented that plantain content is challenging to maintain at levels sufficient to reduce N losses (Dodd et al. 2019; Dodd et al. 2025), annual broadcasting has shown to be effective at maintaining plantain in the sward and something to consider as an integral part of the management practice for a diverse pasture (Fransen et al. 2025).

Despite declines in legumes and herbs within both pasture types, it is important to acknowledge that grass species diversity persisted within the diverse swards throughout the study. In both pasture types grazing management and frequency was similar and perennial ryegrass was the dominant grass species. However, other grass species continued to contribute 20±1.8% to the diverse sward in Waikato and Canterbury, and 7±1.8% in Otago in the final year (Table 4). Of the other grasses, tall and meadow fescue and prairie grass contributed the most to the pasture sward in the Waikato, tall and meadow fescue contributed the most in Canterbury, and prairie grass contributed the most in Otago. These grass species can offer additional benefits, for example, fescue is a deep rooting grass, providing tolerance to drought (Rollo et al. 1998) as well as to common pasture pests (Milne 2011).

Soil health, with the exception of the Otago farms which were established on ex-fodder beet paddocks, was generally good on the dairy farms prior to the establishment of treatments (Figure 4). The establishment of permanent pastures in Otago resulted in improvements in soil health, with soil physical condition improving within the first year after sowing, and earthworm numbers improved in 2025. In contrast, the process of pasture renewal led to declines in some soil health values on the Canterbury farms (e.g., Olsen P, total soil organic C and N) (,Schon et al. 2024). This can be expected as a result of pasture renewal with cultivation (McDowell et al. 2010; Wall et al. 2023a; Wall et al. 2023b). On these farms, total soil organic C remained below pre-establishment levels in winter 2025 (4.8±0.1% vs. 4.1±0.1%), but there were no treatment differences at the final sampling. The lack of differences in the soil, which were generally in good health, may reflect few differences in herbage accumulation and the percentages of grass, legumes and herbs across pasture treatments during the three year study. In this study only changing a few management practices over a short period of time did not impact the soil health indicators measured, and incorporating a wider variety of long-term management changes within a systems context may lead to improved outcomes (Liang et al. 2025; Patil et al. 2025).

Conclusions

Overall, sowing of a more diverse pasture did not influence pasture yields when sown on dairy farms across three regions. Reducing N inputs tended to reduce pasture yields, but that difference declined over the course of the study. The most consistent pasture response to N was seen in Canterbury under irrigation. There was a small, non-significant, increase in white clover content as N inputs were reduced, increasing potential biological N fixation. Although plantain did not persist in the pasture swards, sown grass species (other than perennial ryegrass) continued to contribute meaningfully to sward diversity after three years. The absence of observable impacts on soil health aligns with the small differences found in both the herbage accumulation and sward composition of grass, legumes and herbs between pasture type and N fertiliser treatments.

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REFERENCES

Arp JTT, Sanyal D, Kaur J, Karki D, Bly A. 2026. Exploring the nexus between regenerative agriculture and soil health: a special emphasis on semi-arid and arid agriculture. *Frontiers in Agronomy Volume 8*: https://doi.org/10.3389/fagro.2026.1666008

Black AD, Murdoch HM. 2013. Yield and water use of a ryegrass/white clover sward under different nitrogen and irrigation regimes. *Proceedings of the New Zealand Grassland Association 75*: 157-164. https://doi.org/10.33584/jnzg.2013.75.2916

Blakemore LC, Searle PL, Daly BK. 1987. *Methods for Chemical Analysis of Soils*. New Zealand Soil Bureau Scientific Report 80, 495 p.

Bremner JM. 1996. Nitrogen-Total. In: Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME. *Methods of Soil Analysis*, pp. 1085-1121. SSSA Book Series: Soil Science Society of America. https://doi.org/10.2136/sssabookser5.3.c37

Burchill W, James EK, Li D, Lanigan GJ, Williams M, Iannetta PPM, Humphreys J. 2014. Comparisons of biological nitrogen fixation in association with white clover *(Trifolium repens* L.) under four fertiliser nitrogen inputs as measured using two 15N techniques. *Plant and Soil 385*: 287-302. https://doi.org/10.1007/s11104-014-2199-1

Cameron KC, Di HJ, Moir JL. 2013. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology 162*: 145-173. https://doi.org/10.1111/aab.12014

Chapman D, Parsons A, Schwinning S. 1996. Management of clover in grazed pastures: expectations, limitations and opportunities. *White Clover: NZ's Competitive Edge: Grassland Research and Practice Series 6*: 55-64. https://doi.org/10.33584/rps.6.1995.3378

Chapman DF, Mackay AD, Caradus JR, Clark DA, Goldson SL. 2025. Pasture productivity in New Zealand 1990–2020: trends, expectations, and key factors. *New Zealand Journal of Agricultural Research 68*: 1221-1264. https://doi.org/10.1080/00288233.2024.2425071

Cowling DW, Lockyer DR. 1965. A comparison of the reaction of different grass species to fertilizer nitrogen and to growth in asscoaition with white clover *Grass and Forage Science 20*: 197-204. https://doi.org/10.1111/j.1365-2494.1965.tb00423.x

Crush JR, Cosgrove GP, Brougham RW. 1982. The effect of nitrogen fertiliser on clover nitrogen fixation in an intensively grazed Manawatu pasture. *New Zealand Journal of Experimental Agriculture 10*: 395-399. https://doi.org/10.1080/03015521.1982.10427906

Dignam BEA, Marshall SDG, Wall AJ, Mtandavari YF, Gerard EM, Hicks E, Cameron C, Aalders LT, Shi S, Bell NL. 2022. Impacts of soil-borne disease on plant yield and farm profit in dairying soils. *Journal of Sustainable Agriculture and Environment 1*: 16-29. https://doi.org/10.1002/sae2.12009

Dodd MB, Moss RA, Pinxterhuis IJB. 2019. A paddock survey of on-farm plantain use. *Journal of New Zealand Grasslands 81*: 67-72. https://doi.org/10.33584/jnzg.2019.81.408

Dodd MB, Pinxterhuis IB, Judson HG. 2025. Narrow-leaved plantain (*Plantago lanceolata* L.): A review of research on forage management within temperate grazing systems. *Grassland Research 4*: 41-56. https://doi.org/10.1002/glr2.12107

Dodd MB, Rodriguez-Firpo F, Hedley P, Duker A, Chandler D. 2022. Performance of plantain pastures on Tararua dairy farms. *Journal of New Zealand Grasslands 84*: 67–72. https://doi.org/10.33584/jnzg.2022.84.3573

Donovan M. 2022. Modelling soil loss from surface erosion at high-resolution to better understand sources and drivers across land uses and catchments; a national-scale assessment of Aotearoa, New Zealand. *Environmental Modelling & Software 147*: 105228. https://doi.org/10.1016/j.envsoft.2021.105228

ECan. *Environment Canterbury Regional Council Rainfall data*. https://www.ecan.govt.nz/data/rainfall-data

ESNZ. *National Climate Database*. https://niwa.co.nz/climate-and-weather/national-climate-database

Fransen K, Farrell L, Wheadon N, Rodriguez-Firpo F, Pinxterhuis I. 2025. Using plantain (*Plantago lanceolata*) with other on-farm strategies to meet N loss reduction targets while maintaining profit in Rotorua Lake catchment. *Journal of New Zealand Grasslands 87*: 301-313. https://doi.org/10.33584/jnzg.2025.87.3847

Ghani A, Dexter M, Perrott KW. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biology and Biochemistry 35*: 1231-1243. https://doi.org/10.1016/s0038-0717(03)00186-x

Gray C. 2023. Nitrogen fertiliser use in grazed pasture-based systems in New Zealand: a summary. *New Zealand Journal of Agricultural Research*: 1-52. https://doi.org/10.1080/00288233.2023.2198719

Hawes C, Christie A, Banks G, Boldrin D, Brandt J, Iannetta PP, Swyst I, Turner I. 2025. Long-term regenerative practices enhance in-field biodiversity and soil health for sustainable crop yields. *Frontiers in Sustainable Food Systems Volume 9*: https://doi.org/10.3389/fsufs.2025.1651686

Houlbrooke DJ, Paton RJ, Littlejohn RP, Morton JD. 2011. Land-use intensification in New Zealand: effects on soil properties and pasture production. *Journal of Agricultural Science 149*: 337-349. https://doi.org/10.1017/S0021859610000821

Kankanamge KE, Ramilan T, Tozer PR, de Klein C, Romera A, Pieralli S. 2025. Greenhouse gas mitigation in pasture-based dairy production systems in New Zealand: A review of mitigation options and their interactions. *Climate Smart Agriculture 2*: 100071. https://doi.org/10.1016/j.csag.2025.100071

Keeney DR, Bremner JM. 1966. Characterization of mineralizable nitrogen in soils. *Soil Science Society of America Journal 30*: 714-719. https://doi.org/10.2136/sssaj1966.03615995003000060018x

Khangura R, Ferris D, Wagg C, Bowyer J. 2023.

Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability 15*: 2338. https://doi.org/10.3390/su15032338

Ledgard SF, Brier GJ, Littler RA. 1987. Legume production and nitrogen fixation in hill pasture communities. *New Zealand Journal of Agricultural Research 30*: 413-421. https://doi.org/10.1080/00288233.1987.10417951

Ledgard SF, Sprosen MS, Steele KW. 1996. Nitrogen fixation by nine white clover cultivars in grazed pasture, as affected by nitrogen fertilization. *Plant and Soil 178*: 193-203. https://doi.org/10.1007/BF00011583

Ledgard SF, Sprosen MS, Penno JW, Rajendram GS. 2001. Nitrogen fixation by white clover in pastures grazed by dairy cows: Temporal variation and effects of nitrogen fertilization. *Plant and Soil 229*: 177-187. https://doi.org/10.1023/A:1004833804002

Liang X, Yu S, Ju Y, Wang Y, Yin D. 2025. Integrated Management Practices Foster Soil Health, Productivity, and Agroecosystem Resilience. *Agronomy 15*: 1816. https://doi.org/10.3390/agronomy15081816

Lucas RJ, Smith MC, Jarvis P, Mills A, Moot DJ. 2010. Nitrogen fixation by subterranean and white clovers in dryland cocksfoot pastures. *Journal of New Zealand Grasslands 72*: 141-146. https://doi.org/10.33584/jnzg.2010.72.2825

McDowell RW, Knowler K, Cosgrove G. 2010. Establishment of a split grass-clover system to improve water quality and profitability. *Proceedings of the New Zealand Grassland Association 72*: 171-176. https://doi.org/10.33584/jnzg.2010.72.2808

McGrath JM, Penno JW, MacDonald KA, Carter WA. 1998. Using nitrogen fertiliser to increase dairy farm profitability. *Proceedings of the New Zealand Society of Animal Production 58*: 117-120.

Milne GD. 2011. Can pasture persistence be improved through the use of non ryegrass species? *Pasture Persistence Symposium– Grassland Research and Practice Series 15*: 157-162. https://doi.org/10.33584/rps.15.2011.3197

Ministry for the Environment. 2021. *Understanding the synthetic nitrogen fertiliser cap*. Publication number: INFO 1032. www.environment.govt.nz

Olsen SR, Cole CV, Wanatabe FS, Dean LA. 1954. *Estimation of available phosphorus in soils by extraction with sodium hydrogen carbonate*. U.S.D.A. Circular 939.

Patil M, Perumal C, Choudhari P, Pasumarthi R, Sawargaonkar G, Singh R. 2025. Differential impacts of regenerative agriculture practices on soil organic carbon: a meta-analysis of studies from India. *Scientific Reports 15*: 33470. https://doi.org/10.1038/s41598-025-12149-6

Pinxterhuis JB, Judson HG, Peterson ME, Navarrete S, Minnée E, Dodd MB, Davis SR. 2024. Implementing plantain (*Plantago lanceolata*) to mitigate the impact of grazing ruminants on nitrogen losses to the environment: A review. *Grass and Forage Science 79*: 144-157. https://doi.org/10.1111/gfs.12649

R Core Team. 2024. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rollo MD, Sheath GW, Slay MWA, Knight TL, Judd TG, Thomson NA. 1998. Tall fescue and chicory for increased summer forage production. *Journal of New Zealand Grasslands 60*: 249-253. https://doi.org/10.33584/jnzg.1998.60.2284

Rowarth J, Manning M, Roberts A, King W. 2020. New-generative agriculture - based on science, informed by research and honed by New Zealand farmers. *Journal of New Zealand Grasslands 82*: 221-229.

S-Map. *S-Map Online: The digital soil map for New Zealand*. https://smap.landcareresearch.co.nz/

Schon NL, Roberts A. 2020. *Farm Soil Health: assessment across a forestry to pasture chronosequence* https://ourlandandwater.nz/, 47 p.

Schon NL, Mackay AD. On-farm soil health assessment protocol to aid decision making. In: Christensen CL, Horne DJ, Singh R (Ed). Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. https://flrc.massey.ac.nz/publications.html. Pp. 7.

Schon NL, Mackay AD, Dodd M, Moss RA, Laurenson G, Taylor A, Moorhead A. 2024. Influence of diverse pasture species and reduced nitrogen fertiliser inputs on soil health on four irrigated Canterbury dairy pastures. *Journal of New Zealand Grasslands 86*: 87-95. https://doi.org/10.33584/jnzg.2024.86.3675

Selbie DR, Buckthought LE, Shepherd MA. 2015. The challenge of the urine patch for managing nitrogen in grazed pasture systems. *Advances in Agronomy 129*: 229-292. https://doi.org/10.1016/bs.agron.2014.09.004

Shepherd TG. 2000. *Visual Soil Assessment: Field guide, cropping and pastoral grazing on flat to rolling country*: horizons.mw Report Number 20/EXT/245. Landcare Research, Palmerston North, https://www.landcareresearch.co.nz/publications/vsa-field-guide, 84 p.

Steele KW. 1982. Nitrogen fertilisers in New Zealand agriculture. In: Lynch PB Ed. *Nitrogen in grassland soils*, pp. 29-44. New Zealand Institute of Agricultural Science.

Sutharsan R, Jeyakumar P, Burkitt L, Matse DT, Dhanuskodi R, Hanly J, Donaghy DJ. 2025. Enhancing biological nitrogen fixation through diverse pasture swards. *Plants 17*: https://doi.

org/10.3390/plants14172727

Tozer K, Greenfield R, Howarth S, Farouk M, Bayliss T. 2023. A survey comparing regeneratively and conventionally managed pastures and farm management policies. *Journal of New Zealand Grasslands 84*: 155-164. https://doi.org/10.33584/jnzg.2022.84.3576

Upsdell MP. 1996. Choosing an appropriate covariance function in bayesian smoothing. In: Bernardo JM, Berger JO, Dawid AP, Smith AFM, Bernardo JMet al. Ed. *Bayesian Statistics 5: Proceedings of the Fifth Valencia International Meeting*. Oxford University Press. https://doi.org/10.1093/oso/9780198523567.003.0055

Vibart RE, Vogeler I, Dodd M, Koolard J. 2016. Simple versus diverse temperate pastures: Aspects of soil-plant-animal interrelations central to nitrogen leaching losses. *Agronomy Journal 108*: 2174-2188. https://doi.org/10.2134/agronj2016.04.0193

Walker TW. 1996. The value of N-fixation to pastoral agriculture in New Zealand. *White Clover: NZ's Competitive Edge: Research and Practice Series 6*: 115-118. https://doi.org/10.33584/rps.6.1995.3349

Wall AM, Goodrich JP, Campbell DI, Morcom CP, Schipper LA. 2023a. The carbon balance of a temperate grazed pasture following periodic maize silage cropping depends on climate and management. *Agriculture, Ecosystems & Environment 352*: 108523. https://doi.org/10.1016/j.agee.2023.108523

Wall AM, Wecking AR, Goodrich JP, Pronger J, Campbell DI, Morcom CP, Schipper LA. 2023b. Paddock-scale carbon and greenhouse gas budgets in the first year following the renewal of an intensively grazed perennial pasture. *Soil and Tillage Research 234*: 105814. https://doi.org/10.1016/j.still.2023.105814