Influence of diverse pasture species and reduced nitrogen fertiliser inputs on soil health on four irrigated Canterbury dairy pastures

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Abstract

Maintaining and improving the health of pastoral soils is important to enable the provision of ecosystem services for sustainable production. We investigated the impacts of increasing pasture species diversity and reducing nitrogen (N) fertiliser inputs on pasture productivity and the flow on effects for soil health on four irrigated dairy farms in Canterbury.

The soils had generally good health prior to pastures being resown. During the establishment of both simple and diverse pastures there was a decline in Olsen P, soil organic carbon (C), total N and available N to below target levels. In the year following pasture establishment there was no difference in herbage accumulation between the simple and diverse pastures under irrigation. For both simple and diverse pastures, grass species contributed approximately 50%, legumes 15%, and herbs 20% of the total dry matter harvested. Although there was a reduction in pasture growth as N fertiliser inputs were reduced, legume content did not change significantly and differences in soil health were not observed at this stage.

Despite the farms being intensive dairy systems, the data suggest good soil health prior to pasture establishment. Hence maintaining soil health as well as its restoration following disturbance present opportunities for these farms.

Keywords: cultivation, fertility, multispecies, organic carbon, production

Introduction

There is increasing recognition of a wider range of soil properties, beyond nutrient fertility, and their importance within our farm systems. This more holistic approach is captured by the concept of ‘soil health’, defined as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” (USDA 2012). Healthy soils are better placed to deliver sustainability outcomes for the farm and environment, by supporting essential ecosystem services underpinning a soil’s natural productive capacity (Dominati et al. 2010) and providing increasing resilience to extreme events. Soils are dynamic and degradation can occur in response to both human (e.g., management practices) and environmental influences (e.g., climate) (Bünemann et al. 2018), compromising their ability to provide ecosystem services.

There is evidence indicating that soil physical health and phosphorus (P) fertility (Ministry for the Environment & Statistics NZ 2021) of some of our more intensively managed pastoral soils are outside the range for optimum performance. Soils are less efficient in the use of inputs when degraded (Mackay et al. 2010) and represent greater risks to receiving waterbodies (Monaghan et al. 2005). Developing practices that maintain or improve soil health is important to ensure that agricultural soils retain their inherent productive capacity, make optimum use of inputs and deliver the full range of services.

Increasing plant species diversity has been proposed as one practice to improve soil health. Plant diversity impacts the belowground soil microbial and faunal biodiversity to varying degrees (Millard and Singh 2010). In mown grasslands, increases in pasture species diversity have been reported to increase soil organic carbon (C) and microbial biomass (Reed and Morrissey 2022). Numerous international studies have shown a range of beneficial effects of plant diversity on soil and ecosystem functions which appear to get stronger as the length of study increases (Allan et al. 2013). Increased above and belowground diversity has also been linked to increased resilience within an ecosystem (Wardle et al. 2005).

There have been few New Zealand studies on the impact of increasing pasture diversity on soil function. McNally et al. (2015) identified greater root mass and C inputs from a six-species sward than a two-species sward, but a more recent New Zealand study under irrigation found greater losses of C from a five-species sward than a perennial ryegrass and white clover pasture (Laubach et al. 2023). The impact of diverse

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pastures is likely to be dependent on pasture species sown, how they are managed, and maintained through time (Pembleton et al. 2015), as these factors influence plant size and rooting depth of the different species, and litter returned to the soil. Most sward diversity studies of relevance to New Zealand pastures have compared perennial ryegrass and white clover with swards containing 3–6 species (Vibart et al. 2016). In recent years, diverse pasture mixes containing upwards of fifteen species have been sown under regenerative management principles (Tozer et al. 2023), with the expectation of benefits to soil health.

Decreasing dependency on nitrogen (N) fertiliser application has also been suggested as another practice to improve soil health. Nitrogen fertiliser increases pasture growth and reduces biological N_2 fixation by legumes. The reduction in clover growth and an increase in the grass component of the sward is a feature of pasture under high fertiliser N inputs (Harris and Clark 1996). High rates of N application can also decrease soil pH and microbial biomass (Treseder 2008; Zhang et al. 2018). Regulations restricting N fertiliser use on pastoral farms in New Zealand to 190 kg N/ha/year (Ministry for the Environment 2021) aim to minimise environmental impacts by reducing losses to receiving environments. Reductions in N inputs beyond regulated limits may further benefit legumes and associated biological N_2 fixation (Gray 2023).

This study was initiated to investigate the impact of increasing sown pasture species diversity whilst also reducing N fertiliser inputs on pasture productivity and the flow-on effects on soil health on irrigated Canterbury dairy farms.

Materials and Methods

Four irrigated dairy farms in mid-Canterbury were involved in the study. Two farms were located on stony Pallic Firm Brown soils (Lismore) and two on Argillic Orthic Gley soils (Waterton and Longbeach). The farms had a productive area ranging from 255 to 443 ha, with stocking rates 3–4 cows/ha. Prior to the establishment of the treatments, milk production ranged from 380–520 kg of milk solids (MS)/cow and 1,380–2,100 kg MS/ha. The dairy cows were wintered off farm.

Pastures were established during summer 2021–2022 following cultivation (plough and disc) with one paddock on each farm sown with a 'simple' three-species pasture and an adjacent paddock on the same soil type sown with a 'diverse' pasture (the 'pasture type'). See Table 1 for details on species and sowing rates. The simple pasture contained plantain as this was the typical standard pasture across the study farms. Individual applications of 30 kg N/ha as urea (46% N) were applied (the 'N rate' treatment), with half of each paddock receiving either a low N fertiliser rate (60–90 kg N/ha/year), with an application in spring and again in autumn, or a 'standard' N fertiliser rate (150–180 kg N/ha/year), with applications throughout the 2022–2023 season.

Soil samples were collected along a transect for each treatment once prior to pasture establishment (2021) and then annually in winter (2022 and 2023). Soil cores (20 cores of 25 mm diameter, 0–75 mm depth) were bulked and sent to a commercial laboratory (RJ Hill Laboratories, www.hill-labs.co.nz) for analysis of soil pH (1:2.5 soil: water), Olsen P (Olsen et al. 1954), calcium (Ca), magnesium (Mg), sodium (Na), sulphate-sulphur (SO_4-S), organic sulphur (OS), hot water extractable C(HWEC) (Ghani et al. 2003), anaerobically mineralizable N (AMN) (Keeney and Bremner 1966), total soil organic 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 score also includes an assessment of earthworm abundance from a 200 mm × 200 mm × 200 mm soil sample by hand-sorting. In addition, earthworm biomass was 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 also identified, including porina (*Wiseana cervinata*), grass grub (*Costelytra zealandica*) and clover root weevil (*Sitona lepidus*). All measures had associated targets for use as soil health indicators (Schon and Mackay 2023).

Pasture cages were used to assess herbage dry matter (DM) accumulation and estimate monthly and annual yields during the 2022–2023 season. Pasture cages were placed in representative sites (three per treatment). After each grazing, the accumulated herbage within pasture cages was assessed within a 0.5 m^2 quadrat by trimming herbage to ground level. Alongside the pasture cage, 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 position. Herbage was washed to remove extraneous matter and dried (at 95°C for 48 hours) to determine total DM. Each season, a sub-sample of approximately 400 pieces was collected from the harvested herbage to identify pasture species and dead matter, and from the residual sample to quantify the dead material. Additionally, bulk subsamples were collected from both the pre- and post-graze samples for chemical analysis. Herbage was dried at 50°C for 24 hours and sent to a commercial laboratory (RJ Hill Laboratories) for analysis of crude protein (CP), total N (Dumas combustion) and metabolizable energy (ME) estimated by near infrared spectroscopy (NIR). Total herbage DM and monthly herbage accumulation rates

Table 1 Seed mix and sowing rate (kg/ha) for the simple and diverse pastures.

Species	**Cultivar**	**Sowing Rate**	
		Simple	**Diverse**
Perennial ryegrass *(Lolium perenne* L.*)* - 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	2
Chicory *(Cichorium intybus)*	Choice		1

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

were calculated during the 2022–2023 milking season.

Statistical analysis assessed changes in soil variables from baseline using one-sample t-tests performed using statistical software Minitab (version 16.2). Cumulative pasture growth, post-graze residuals, monthly growth rates and seasonal data were compared between treatments across farms in a split-plot analysis of variance (ANOVA). The split-plot ANOVA consisted of farm effects for blocking, and pasture type and N rate effects as main plot factor and sub-plot factor, respectively. A second ANOVA was conducted to compare pasture cumulative pasture growth and post-graze residuals between farms by ANOVA. Each ANOVA consisted of only farm effects for comparison. The ANOVAs were carried out in statistical software Genstat (20th edition).

Results

Prior to the establishment of the pastures many of the measured soil indicators on the four dairy farms were near- or within-target ranges (Table 2). There was an average decline in some soil indicators during the establishment of the pastures, with Olsen P, Ca, sulphate-S, total organic C, total N, AMN and HWEC all lower in 2022 than 2021. By 2023 some properties had started to recover towards levels seen in 2021, but differences in total organic C, total N and AMN remained lower than prior to pasture establishment. The drop in Olsen P, total and AMN moved these indicators from near- or within-target ranges to below-target ranges. Following a wet winter in 2022 with 176 mm rainfall in July (260% above the long-term average), there was a decline in the VSA score in the winter of 2023, with this indicator dropping from within to below target. This corresponded to a decline in soil macroporosity from 13% to 10.5% on the Gley soils. No significant differences in any soil health indicators were found between the four pasture and N treatments 1 year after establishment, hence results are shown as annual averages.

During the 2022–2023 season, paddocks were grazed on average nine times. Average daily pasture accumulation rates in each month for treatments are presented in Figure 1. Cumulative annual pasture yield averaged 22,500 kg DM/ha across three farms, with lower pasture yields on one farm (19,800 kg DM/ha/year, $P<0.05$). Although the farm with lower pasture yields also had lower post-graze residuals (<1,200 kg DM/ha vs. >1,800 kg DM/ha, $P<0.05$), there was another farm which also had lower post-graze residuals but did not have lower pasture yields. Low levels of Olsen P may be contributing to the lower pasture yields observed.

Table 2 Average values across all treatments for 21 soil health indicators on four irrigated Canterbury dairy farms prior to (2021) and following (2022 and 2023) the establishment of treatments (standard error of mean shown in parenthesis). Target values from Schon and Mackay (2023) are provided.

Soil Indicator	Target	2021	2022	2023
pH	5.8–6.0	6.3 (0.2)	**6.2 (0.1)***	6.3 (0.04)
Olsen P (μg/ml)	20–40	19.9 (0.4)	**13.6 (1.8)***	16.8 (1.3)
K (MAF QT)[1]	5–8	8.1 (0.6)	7.7 (0.9)	8.9 (0.8)
Ca (MAF QT)[1]	>1.5	12.6 (0.9)	**10.9 (1.0)***	11.9 (0.9)
Mg (MAF QT)[1]	8–10	40.9 (3.2)	**34.4 (4.2)***	**36.8 (3.2)***
Sulphate-S (mg/kg)	10–12	14.7 (2.3)	**5.7 (1)***	**10.1 (0.8)***
Organic S (mg/kg)	15–20	6.8 (0.1)	**5.6 (0.3)***	**5.9 (0.3)***
Total organic C (%)	>3.5	4.8 (0.1)	**3.6 (0.2)***	**3.4 (0.2)***
Total N (%)	0.35–0.65	0.41 (0.01)	**0.29 (0.02)***	**0.30 (0.02)***
Soil C:N ratio	8–12	11.7 (0.3)	12.2 (0.4)	11.4 (0.5)
Anaerobically mineralizable N (μg/g)	100–200	135 (7)	**85 (5)***	**85 (5)***
Hot water extractable C (mg/kg)	>1,400	2,427 (71)	**1,453 (87)***	2,022 (124)
Visual Soil Assessment[2]	20	20.4 (0.7)	20.7 (0.8)	**16.4 (1)***
Bare soil and surface relief[2]	2	4.7(0.2)	**4.2 (0.04)***	4.3 (0.2)
Colour and mottles[2]	2	7.8 (0)	7.7 (0.1)	7.8 (0.1)
Structure and porosity[2]	2	7.7 (0.3)	7.8 (0.4)	7.1 (0.9)
Total earthworm abundance (per m^2)	>400	449 (72)	392 (17)	408 (22)
Earthworm diversity[3]	3	1.6 (0.1)	1.7 (0.1)	2.0 (0.04)
Porina (per m^2)	<20	0.5 (1)	0.0 (0)	**2.1 (1.2)***
Grass grub (per m^2)	<150	6.8 (7)	4.7 (1)	7.3 (3.1)
Clover root weevil larvae (per m^2)	<130	11 (3)	33 (16)	**33 (4)***

* Denotes a value significantly different from that measured in 2021 ($P<0.05$).

[1] MAF QT refers to the MAF Quicktest (Cornforth and Sinclair 1984).

[2] Each individual visual indicator has a maximum score of 2, with a total VSA score target of 20.

[3] Number of earthworm ecological groups present, from a total of three.

There was no difference in annual pasture yield and monthly mean pasture growth rates between the simple and diverse pastures. However, there was significantly more pasture grown in the standard N than the low N treatments. On average, standard N produced an extra 800 kg DM/ha from the simple pasture ($P<0.05$) and an extra 1,900 kg DM/ha from the diverse pasture ($P<0.05$). This translated into 9 and 20 kg DM/kg N for the simple pastures and diverse pastures, respectively. The pasture response to N fertiliser was greater ($P<0.05$) on the stony Lismore soils than on the Gley soils (24 kg DM/kg N vs. 4 kg DM/kg N respectively). There were no differences in post-graze residuals between treatments (Figure 2).

Pasture species composition changed throughout the growing season. In all swards, grass species contributed approximately 50%, legumes 15% and herbs 20% of the total DM harvested. The highest percentage of grass was seen in winter and spring (60–63%, $P<0.02$) and the highest percentage of legumes in summer (26%, $P<0.01$) (Figure 3). There were significantly more herbs in spring under low N fertiliser regime in the diverse than simple pastures (29 vs. 19%, respectively, $P<0.05$). Of the species that were sown across both treatments, ryegrass made up 79% (by weight) in the simple seed mix and 24% in the diverse seed mix, and although the percent of ryegrass was higher in the simple mix initially, the ryegrass percent in the pasture had reduced to levels similar in the diverse pasture by autumn. White clover constituted 10–14% (by weight) in the diverse and simple seed mixes, respectively, but contributed up to 20% in the pasture. Plantain constituted 5% and 7% (by weight) in the diverse and simple seed mixes, respectively, but contributed up to 23% in the pasture

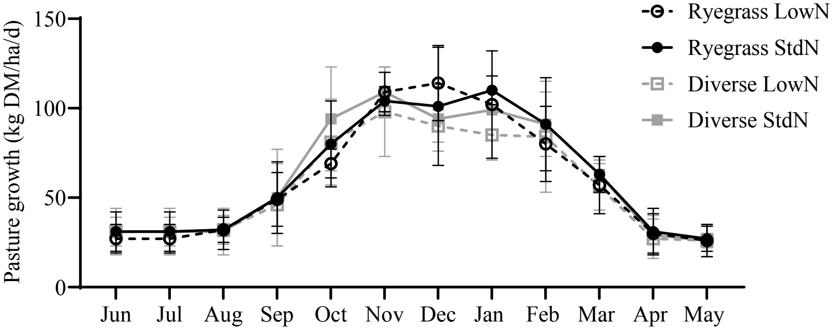

Figure 1 Average monthly pasture accumulation rates (kg DM/ha/day) for four pasture type × N rate treatments during 2022–2023 on four irrigated Canterbury dairy farms. Bars represent standard errors of means.

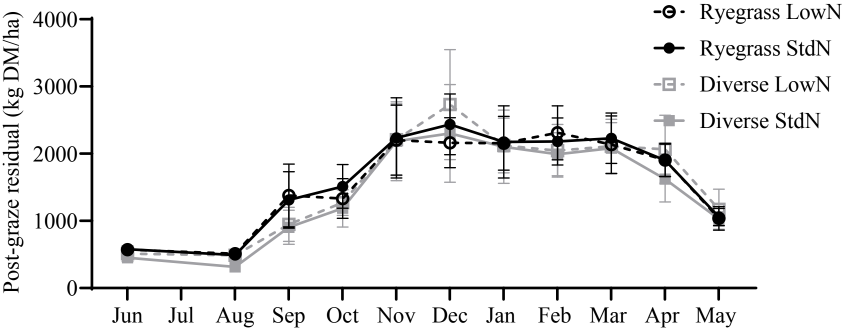

Figure 2 Average monthly post-graze herbage residuals (kg DM/ha) for four pasture type × N rate treatments during 2022–2023 on four irrigated Canterbury dairy farms. Bars represent standard errors of means.

sward across the seasons. In the diverse pastures all sown species were observed, with lucerne and vetch the least common in the diverse pastures.

In spring the N content of the herbage in diverse pastures was higher for standard N than low N (2.35% vs. 2.08%, respectively, $P<0.05$). At this time there was also a higher ME in the diverse than in the simple pastures under standard N rates (11.1 vs. 10.7 MJ/kg DM respectively, $P<0.05$, Figure 4). Post-graze residuals of the diverse pastures in winter and summer had higher N content in the standard N than in the low N treatment (2.18% vs. 2.03% in winter, and 1.98% vs. 1.73% in summer, respectively, $P<0.05$).

Discussion

Soil health across both soils on the four irrigated dairy farms was generally good prior to the establishment of pasture treatments. Most indicators across all aspects of soil health, including soil fertility, organic matter properties, soil physical condition and biological activity were near or at target for each soil type indicating limited scope for improvement. This contrasts State of Environment reporting which found Olsen P to be above optimal in 61% of sites monitored (Ministry for the Environment and Statistics NZ 2021), with Olsen P at the low end of the target range on the study farms. Poor soil physical condition has also often been of concern in dairy pastures (Hu et al. 2021), however the VSA scores indicate soil physical condition was not restricting these soils function and delivery of services prior to treatments being imposed.

Pasture establishment resulted in a decline in soil fertility and organic matter properties, with reductions in Olsen P, soil organic C, total N and AMN remaining for more than 1 year after sowing. Indeed, the combination of cultivation with a period of no plant growth during pasture renewal increases losses of soil C (Wall et al. 2023a; Wall et al. 2023b) and N (Trolove et al. 2019). It also appears the mixing and potential dilution of the topsoil through cultivation also effectively reduced levels of available P (McDowell et al. 2010). Future sampling will track how different pasture mixtures and N fertiliser regimes influence the recovery of the indicators impacted by cultivation.

Although there was no difference in pasture production between the simple and diverse pastures, less herbage

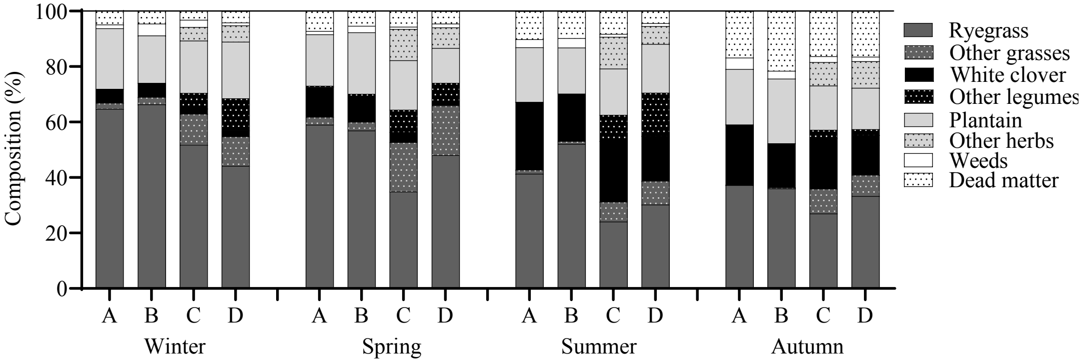

Figure 3 Average pasture composition observed throughout the seasons for four pasture type × N rate treatments (A: ryegrass Low N, B: ryegrass standard N, C: diverse Low N, and D: diverse Standard N) during 2022–2023 on four irrigated Canterbury dairy farms.

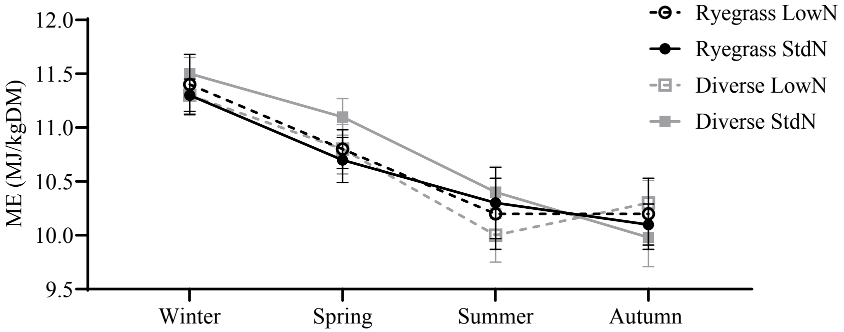

Figure 4 Average metabolizable energy (ME, MJ/kg DM) in each season during 2022–2023 for four pasture type × N rate treatments on four irrigated Canterbury dairy farms. Bars represent standard errors of means.

was grown when N fertiliser inputs were reduced as has been shown in many other studies (Shepherd and Lucci 2011; Gray 2023). The lower pasture growth under the low N potentially translated into less plant litter entering the soil system, particularly in late winter and early spring when the biological community is most active. Decreases in pasture growth and potential litter return have been shown to reduce earthworm abundance (Curry et al. 2008). The difference in litter return may be exacerbated on the stony soils where N responses were greater. The low N treatments were also characterised by having lower herbage N% in comparison to standard N treatments in spring, as well as in post-graze residuals in summer and winter. This translates to less litter of lower quality potentially being returned to the soil under low N treatments. Reductions in herbage N can have implications for soil biodiversity (van Eekeren et al. 2010), but also represents a potential opportunity to reduce N losses via leaching and volatilisation from urine patches (Dijkstra et al. 2013; Bryant et al. 2020).

Reductions in clover are expected under higher levels of N fertiliser use (Ledgard et al. 1987), although this was not observed in the first year following pasture establishment on these farms. We expect any differences in legume content to become more evident in the second year after establishment. In the first year after sowing the percentage of the main plant functional types (grass, legumes and herbs) across treatments have been similar. The exception to this was the herb content, which was higher in spring under low N in the diverse than in the simple pastures, likely due to the low sowing rates of the highly competitive ryegrasses, allowing these species to establish and contribute DM at their time of peak growth. This coincided with higher ME in the diverse than in the simple pastures under standard N treatments. A higher ME content will contribute to higher livestock performance, though other studies have shown variable results in this respect (Dodd et al. 2019a). Plantain was the dominant herb across both simple and diverse pastures, contributing up to 23% towards the pasture. However, maintaining plantain at these levels (Minnée et al. 2020; Vi et al. 2023) can be challenging (Dodd et al. 2019b).

The decline in the soil physical condition after winter highlights the vulnerability to degradation of soils in intensive livestock systems. These effects were seen across all treatments, with the more diverse pastures not providing any evidence of resistance to damage. Treading by cattle can lead to compacted soils, especially when soils remain above field capacity (Hewitt and Shepherd 1997; Houlbrooke and Laurenson 2013). Indeed, the impact of grazing during a wet period was still evident the following winter. This has implications not only for pasture growth also for nutrient losses to the environment (Hu et al. 2021). Recovery from soil compaction can take many years (Drewry 2006).

Conclusions

Soil health was generally good across the four irrigated Canterbury dairy farms for the range of indicators assessed prior to the establishment of pasture swards and nitrogen input treatments. However, pasture renewal *via* cultivation resulted in a decline in some soil health indicators to below target levels, with these differences remaining after 1 year. Maintaining existing soil health during wet periods and restoring soil health following disturbance by cultivation present opportunities for these farms.

In the first year following establishment, pasture yield was similar between the simple and diverse pastures with no differences in soil health. The observed reduction in pasture growth with reductions in N inputs, also did not translate into any measurable changes in soil health indicators after 1 year. Further monitoring is required to understand how the impact of diverse pastures and N treatments impact soil health over a longer period.

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