The environmental performance of a pasture and baleage wintering system on a poorly drained soil in southern New Zealand

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Abstract

Concern about environmental and animal welfare outcomes associated with crop-based wintering has prompted interest in the potential feasibility of pasture-based approaches as alternative wintering methods. This interest is especially relevant to southern regions of New Zealand where forage crops are prevalent and soil quality can deteriorate during wet winter conditions. We compared changes in soil condition and nitrogen (N) leaching losses from treatments where mature dairy cows were winter-grazed on either fresh (annual) pasture and baleage or brassica crops as the main sources of dietary feed. These responses were measured from large spatially randomized and hydrologically-isolated mole-pipe drained plots over a three year monitoring period. Considerable soil treading damage was incurred under both wintering treatments. Recovery of pasture in the pasture plots was accordingly slow, particularly in 2021 when soil conditions at the time of plot grazing were relatively wet: four months after grazing, about 30% of plot area remained bare, requiring resowing. Pasture recoveries in 2022 and 2023 were faster, with less than 20% bare ground present 3 months after winter grazing. There were no significant differences in N losses in drainage from the treatments in 2021 and 2022. Significantly more N was leached from the pasture-baleage than the crop treatment in 2023, most likely a consequence of a late autumn grazing that was required to manage pasture quality. Pasture-baleage wintering did not reduce N leaching compared to wintering on crop for this soil type. Whilst measures of soil quality were better under the pasture-based than the crop-based wintering treatment, overall soil condition was assessed as poor for both treatments. A shift from crop to pasture-baleage wintering would appear to offer only modest advantages to soil and water quality when deployed on structurally-vulnerable soils. Other measures to help minimise soil treading damage, such as providing loafing surfaces or using standoff pads during very wet conditions, are likely needed to improve the performance of this pasture-based system on such vulnerable soil types.

Keywords: cattle, nitrate leaching, soil armour, soil inorganic N, soil organic n, winter grazing

Introduction

Winter crops are an important means of providing sufficient feed to animals in southern New Zealand during cooler times when pasture growth is limited. However, such wintering practises can have negative effects on soil quality, contaminant loss to water and air as well as animal welfare status (McDowell and Houlbrooke 2009; Monaghan et al. 2017; van der Weerden et al. 2017; Smith and Monaghan 2020, Neave et al. 2022). One key aspect driving these negative impacts is the amount of treading damage and hence mud generated by cows on grazed fodder crop paddocks (Drewry and Paton 2005).

One approach that is being explored by a number of southern farmers to significantly reduce the extent of muddy paddocks has been to replace fodder crops with all-pasture wintering areas. This approach relies on using standing pasture supplemented with relatively large amounts of baleage to ensure the dietary requirements of the livestock are met. Whilst this approach can also result in relatively high grazing intensities, it does provide at least two potential advantages over fodder crop wintering systems. The first is that soil retains some degree of protection due to the presence of a pasture thatch and root mass that helps to maintain soil cohesion. The root mass and any subsequent pasture regrowth are also likely to provide a sink for taking up some of the urinary N deposited by livestock, thus reducing the risk of N loss to water and air (Talbot et al. 2020). A second perceived advantage to maintaining soil protection or armour is the retention of a cleaner, more stable soil surface that will encourage livestock to rest more frequently and for longer during wet and cool conditions, thus providing positive animal welfare outcomes.

Whilst all-grass wintering systems are nothing new, there is practically no information on possible environmental impacts or consequences for animal welfare. Therefore, their suitability to the range of

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Table 1 Details of treatment sowing times, fertilizer inputs and grazing events at the Telford field site.

	2021		2022		2023	
Treatment	**Swedes**	**Pasture**	**Swedes**	**Pasture**[a]	**Kale**	**Pasture**
Sowing date	10 Dec 2020	10 Dec 2020	23 Nov 2021		7 Nov 2022	7 Nov 2022
N Fertiliser inputs						
At sowing	60 kg N/ha	60 kg N/ha	60 kg N/ha		43 kg N/ha	43 kg N/ha
23 Nov				60 kg N/ha		
20 Jan					46 kg N/ha	46 kg N/ha
23 Feb	46 kg N/ha	46 kg N/ha				
2 March			46 kg N/ha			
23 March	30 kg N/ha					
Pasture shut up for winter		23 Feb		24 Jan[b]		2 May[c]
Winter grazing	22 - 24 June	22 - 24 June	22 – 24 June	22 – 24 June	6 – 8 June	6 – 8 June
First spring grazing		20 Oct		11 Oct		8 Sept

[a] Pasture was not resown - only bare areas of soil were direct-drilled with seed in the pasture treatment to repair damage incurred during grazing in winter 2021

[b] summer drought restricted pasture yields and decreased pasture quality

[c] vigorous growth of the annual pasture required a late autumn grazing to control pasture quality

soils, landscapes and climates currently using all-grass wintering systems in southern New Zealand to minimise these impacts is unclear. A study was therefore undertaken to quantify some of the perceived benefits of a pasture-based approach for wintering as compared to using a traditional brassica crop system.

Materials and Methods

The site for this experiment was located at the Telford dairy farm in South Otago (46° 18′ 01”S 169°44′ 03”E). The soil type is a Timaru Mottled Fragic Pallic soil (Hewitt 2010), classified as imperfectly drained with a high vulnerability to water logging. It has moderate to low soil water holding capacity, with a high structural vulnerability and a moderate N leaching potential.

The experiment was of a randomised block design (seven replicates) with two main treatments: a pasture-baleage wintering approach and a crop-based approach. Individual plot sizes averaged 400 and 484 m^2 in the pasture-baleage and crop treatments, respectively. Some soil fertility attributes for the two treatments were: pH = 6.4; Olsen P = 45-50 mg/L; QT K = 19-23. Details of crop sowing dates are shown in Table 1. Following soil cultivation, new pasture consisting of ‘Shogun’ tetraploid annual ryegrass at 20 kg/ha and Sophia white clover at 6 kg/ha was sown into the pasture-baleage treatment plots in December 2020 (Table 1). Following winter grazing in 2021, about 30% of the pasture plot area remained bare by mid spring. These bare patches were therefore re-sown (direct-drilled) with the same pasture mix in late October 2021. Pasture species composition deteriorated following a severe summer drought and intensive winter grazing in 2022, requiring pasture plots to be re-cultivated with a rota-tiller after spraying in spring. A similar pasture seed mix was then broadcast, and plots harrowed and rolled.

Yield measurements and grazing management

Measurements of crop and pasture yields were conducted prior to each winter grazing. Swede yields in 2021 and 2022 were calculated by harvesting two 1 m^2 quadrats per plot. Bulbs were pulled from the ground and soil removed before weighing. Subsamples of both bulbs and leaves were retained and dried at 65°C for dry matter determination. Kale yields in 2023 were calculated by measuring the height of the crop at 20 locations within each plot. These heights were calibrated with yields by harvesting six 1 m^2 quadrats of different heights, thus establishing a relationship between crop height and yield. All kale plants were cut at ground level. Harvested crops were weighed, with a sub-sample retained and dried at 65°C for dry matter determination. Pasture yields were calculated using two 0.25 m^2 quadrats cut to ground level within each plot. The amount of residual crop or pasture left by the animals following each grazing was determined in the same fashion as pre-grazing yields, with all above ground kale remnants harvested. Differences between pre-grazing crop yields and residuals left after grazing were used as estimates of animal intakes. All dried crop, pasture and baleage samples were sent to a commercial laboratory for N and feed quality (Metabolisable energy (ME)) determination.

The winter grazing treatments were grazed by mature mixed-age cows over three days in June each year (Table 1). Each plot was split into 3 breaks, with the cows grazing break 1 on day 1, breaks 1 and 2 on day 2, and breaks 2 and 3 on day 3. For the pasture treatment, individual plots were stocked at a density equivalent to 13 m^2/cow/day in 2021. The design (space allowance in particular) and management of the experimental treatments were guided by surveys and interactions with selected farmers and rural professionals in Otago who were interested in the performance of the pasture-baleage wintering approach which had been practised by some farmers in the district. Due to the considerable soil and pasture damage observed in this first year of study, space allowance in this treatment was increased to 16 m^2/cow/day for winter 2022 and 2023. Cows in the crop wintering treatment were more densely stocked at 10 m^2/cow/day (consistent for all 3 winters) as determined by targeted crop allocations (kg DM/cow/day) and measured yields. Cows were offered fresh and supplementary feeds that matched feeding allocations for herds elsewhere on the farm. These were:

- Pasture-baleage wintering: fresh pasture equivalent to 5 - 7 kg DM/cow/day; pasture baleage equivalent to 9 kg DM/cow/day.
- Crop wintering: crop equivalent to 10 - 12 kg DM/cow/day; pasture baleage equivalent to 3 - 4 kg DM/cow/day.

All grazing events were conducted under AgResearch Animal Ethics Approval AEC15314.

Drainage sampling

Pre-existing large-scale experimental infrastructure was used to evaluate the effects of the two wintering options. This included automated and dynamic measurement of contaminant transfers via drainage through the mole-pipe drainage systems installed at the site (described in detail by Laurenson et al. 2017). Briefly, leachate sampling was measured by means of tipping buckets that collected drainage from each of the 14 hydrologically-isolated plots that had been established in 2011 (Laurenson et al. 2017). A siphon on one side of the tipping bucket collected and stored 0.2% of each tip volume. Samples were collected following each drainage event and stored frozen before being sent for chemical analysis. Analyses of ammonium-N (NH_4-N), nitrate-N + nitrite-N (hereafter referred to as NO_3-N) and total N (TN) were conducted by a commercial laboratory using standard flow-injection and colorimetric methods (APHA 4500: online edition). Concentrations of total organic nitrogen (TON) were calculated as the difference between TN and the inorganic-N concentrations (NO_3-N + NH_4-N), corrected for the incomplete recovery of NO_3-N by the TN method. Concentrations of filterable (<0.45 µm) reactive P (FRP) and, after persulphate digestion, total dissolved P (TDP) were analysed colorimetrically (APHA 4500). An unfiltered subsample was also measured for total P after persulphate digestion. Particulate P was calculated as the difference between TP and TDP.

A daily time-step water balance model developed by El-Naggar et al. (2020) was used to improve the utility of the FAO 56 - PM model (FAO 2000) and estimate site-specific daily drainage at the site. This model includes a multi-layer soil feature and drainage factors that account in some cases for slower drainage rates and the associated water storage. Daily weather data derived from the Telford meteorological station (located 1 km north-west of the field site) were used to calculate daily evapotranspiration rates (ET). The FAO56 - PM model and a dual crop coefficient method which accounts for variations in soil water availability, inducing either stress or soil evaporation, were used to estimate crop evapotranspiration (ETc) (Allen et al. 1998).

Soil measurements

Various parameters to assess soil quality were measured in both treatments two weeks after the grazing events were completed: (i) Pug depth was measured in 10 locations within each plot replicate using a drop cone penetrometer (Godwin et al. 1991), mimicking the dynamic force delivered by a cow hoof; (ii) Soil roughness was measured using a standard-length chain (Saleh 1993) in two locations within each plot plus one ungrazed location (under the fence); and (iii) Visual soil assessments (VSA; Shepherd 2000) were conducted in October 2022 and before soil re-cultivation to document soil conditions following two years of winter grazing at this site, recognising that longer periods of such use are not recommended for this intensive land use activity. Whilst earthworm numbers contribute to the overall VSA score, they are also a good indicator of soil quality (Schon et al. 2022). Total earthworm numbers were therefore also analysed separately.

Pasture recovery

Pasture recovery for the pasture-baleage plots was measured monthly, commencing two weeks following each winter grazing. Measurements were done using a point analysis frame, measuring ground cover at 10 places along the frame at 10 one metre intervals along a diagonal transect. Ground cover was also assessed via photographs taken from a drone in 2022 and 2023. Pasture yield was measured at the time of the first spring grazing in 2022 and 2023 by the same quadrat method used prior to the winter grazing.

Data analysis

Analyte concentrations in drainage were determined for each individual event and each plot. Losses were calculated by multiplying the concentrations at each event by the modelled drainage volume for that event. All data were analysed by ANOVA using Genstat version 22.

An important aim of the study was to provide a more integrated assessment of impacts than normally undertaken for evaluations of wintering systems to date. The key indicators used are therefore described below with a brief description of how each indicator was derived.

- N leaching loss: this impact metric was calculated to fully consider the potentially confounding effect of required winter areas. This calculation step recognises that the areas needed for wintering animals differ depending on factors such as standing crop (or pasture) yields and daily allocations per cow. Losses were therefore calculated at a whole-farm scale, accounting for differing block areas (milking platform and required winter pasture or crop areas) and measured or assumed N leaching losses for each. The N leaching loss of 20 kg/ha measured at the site and reported by Laurenson et al. (2017) was used for the assumed milking platform area.
- VSA score: undertaken as referred to above.
- Soil loss mitigation: measurements of pasture covers were used to derive vegetation cover (C) factors for use in the Revised Universal Soil Loss Equation (Renard et al. 1997). These calculations were made on a seasonal basis and aggregated to provide an annual estimate of soil loss risk (Donovan and Monaghan 2021). As for N leaching estimates, because of the differing areas of exposed soil this impact metric was also computed at a farm scale to allow comparison between treatments.
- Diesel energy requirements: An inventory of all the tractor operations associated with harvesting, transporting and feeding supplements, establishing a crop and re-sowing fields post winter grazing was compiled for each wintering system. The energy requirements for each of these operations were derived using assumptions documented in Wells (2001), aggregated to an annual total and expressed in units of MJ energy per cow wintered.
- Relative area requirements: these were based on the daily space allocations of 10 and 16 m^2/cow/day used in the crop and pasture-baleage grazing treatments, respectively.

Results and Discussion

Rainfall and drainage

Rainfall totals for 2021, 2022 and 2023 totalled 610, 568 and 598 mm, respectively (Figure 1). These totals are lower than the long term (2010 – 2020) average of 678 mm. Modelled drainage volumes were 198, 188 and 159 mm for the three years. These drainage values are considerably lower than the long term (2010 – 2020) average modelled drainage of 239 mm but are within the range of 140 to 220 mm previously measured at this site (Laurenson et al. 2017). The drainage season went from May to December in 2021, May to November in 2022 and from May to September in 2023. The short drainage season in 2023 was due to a drier October and November (Figure 1). In 2021 and 2022, 51 and 55 mm of rain and 46 and 32 mm of drainage occurred in the 10 days immediately prior to the cows grazing the two treatments for the two years, respectively. In contrast, there was only 5 mm of rain with no drainage prior to the grazing in 2023. In 2021, 68 mm of drainage occurred within three months of the winter grazing, with the majority (67%) of this occurring during or within 24 days of winter grazing. In contrast, drainage volumes in the three months following winter grazing in 2022 and 2023 were considerably higher, totalling 148 mm in 2022 and 132 mm in 2023 and being more evenly spread over this period.

Crop and pasture yields and animal intakes

The crop yields in 2021, 2022 (swedes) and 2023 (kale) were 11, 10 and 12 T DM/ha, respectively (Table 2). The swede crops accounted for 70% of the cows' diet while the kale crop accounted for 74% of total diet (Figure 2A). These figures are in line with previous studies where crop allocations are typically 70 to 80% of the cows' winter diets (Rugoho et al. 2014; Smith and Monaghan 2020).

The dry matter intakes for cows in the pasture-baleage wintering treatment in 2021 were similar to intakes for cows in the crop wintering treatment, but lower in 2022 and again in 2023 (Figure 2A). However, pasture only accounted for 34% of the cows' diet in the pasture-baleage grazing treatment in 2021, 38% in 2022 and 28% in 2023 (Figure2A). These pasture intakes are considerably lower than the 65-80% of pasture in winter diets reported by Rugoho et al. (2014) and Atkins et al. (2018). Despite this, the metabolizable

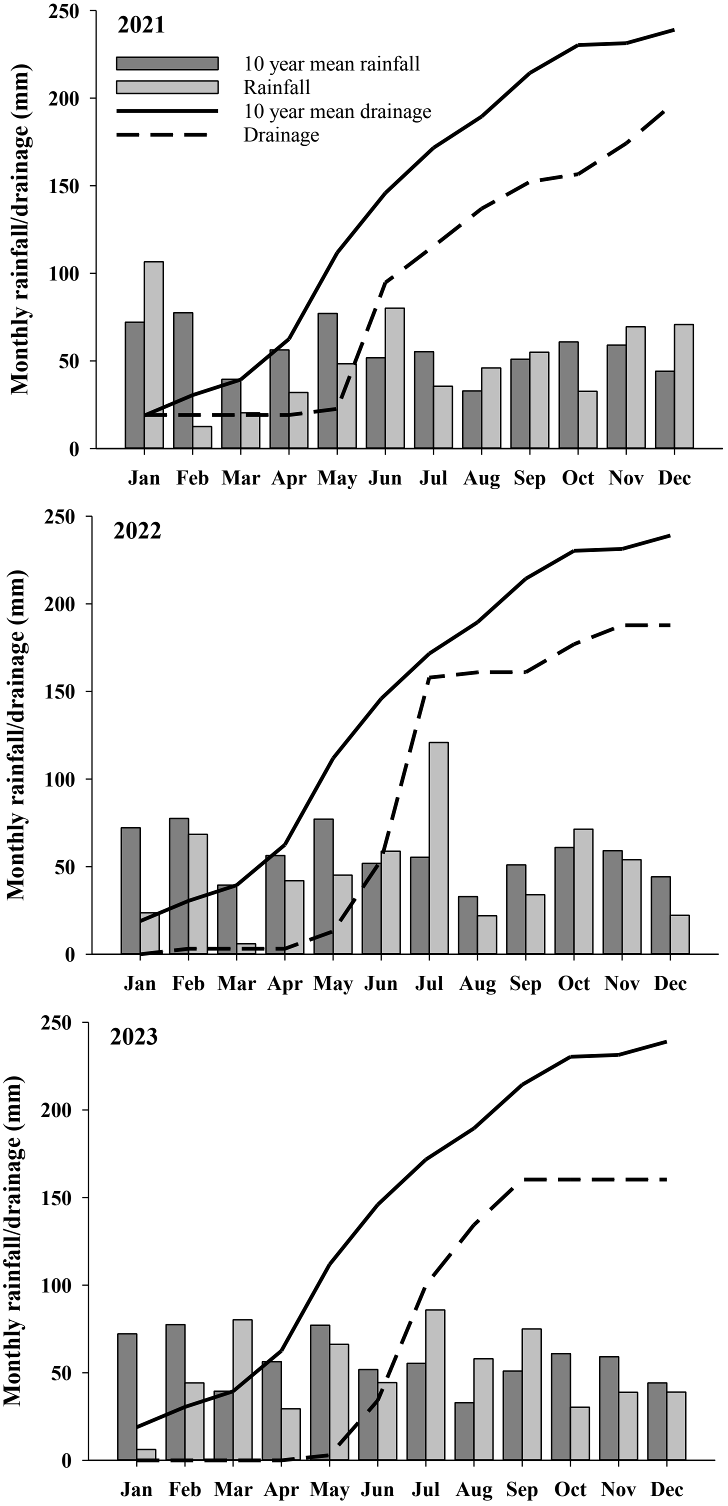

Figure 1 Monthly rainfall (bars) and modelled cumulative drainage patterns (dashed lines) for the Telford site for the three years of measurement. These annual rainfall and drainage results are shown along with calculations of longer term (10-year) means as indicated by the darker shading and solid lines, respectively.

Table 2 Plant yields and nutritional quality of forages offered to cows at the Telford study site in 2021, 2022 and 2023.

Forage	Yield (kg DM/ha)	Nitrogen (%)	ME (MJ kg/DM)	Crude Protein (% DM)	Total Carbon (%)	C:N ratio
2021						
Swedes (grown)	11407	2.0	13.3	12.4	40.2	20.5
Pasture	4470	1.8	10.4	11.2	40.5	22.5
Baleage		2.0	10.0	11.3	39.2	19.6
2022						
Swedes (grown)	10016	1.7	12.7	10.5	42.6	25.4
Pasture	4286	1.9	8.4	11.9	43.9	23.1
Baleage		2.8	11.3	17.5	No data	No data
2023						
Kale (grown)	12162	1.9	11.5	11.6	40.3	25.7
Pasture	1975	4.7	11.5	29.3	37.9	8.1
Baleage		1.6	7.2	10.1	42.7	26.5

energy (ME) levels of the grass and baleage (Table 2) meant that such a diet was sufficient to meet daily ME requirements (Figure 2B). Despite animals on the pasture-baleage plots having lower DM intakes in 2022 and 2023 and lower ME intakes in all three years of study, their estimated intakes of dietary N were similar to those for the cows on crop in 2021 and 2022 and greater in 2023 (Figure 2C).

Soil damage

Measurements of soil roughness and pug depth indicated that soil damage was significantly greater in the crop wintering treatment than in the pasture-baleage wintering treatment (Table 3) in all three years of the study. This was expected as previous studies have shown the link between grazing winter crops and increased soil roughness (McDowell et al. 2005). As expected, due to the wet conditions whilst grazing in the first winter of study, pug depth in 2021 was greater than in 2022 and 2023. Soil roughness in the crop treatment was however noted to be less than measured in 2022 and 2023, presumably due to the liquid deformation and re-distribution of soil induced by poaching instead of hoof pugging (Drewry et al. 2008). The disruption and clogging of soil pores due to this poaching likely accounted for the greater extent of ponding that was visually observed in 2021 and, we could infer, probably elevated the risk of surface runoff.

Visual soil assessment scores (Table 4) indicated that soil condition was generally poor. This was particularly so for the crop wintering treatment. The mean VSA score of 10.8 for the pasture-baleage wintering treatment was also relatively low, despite the presence of some degree of protection provided by the pasture cover and root thatch. As noted by Russell et al. (2001), the presence of pasture does not prevent soil damage, but it can minimise its extent at moderate soil moisture contents. However, Hewitt and Shepherd (1997) found that Pallic soils such as the one at our site are more prone to slaking and dispersion in wet conditions, making them highly vulnerable to structural degradation.

Worm numbers were below the optimum threshold of 400 m^{-2} (Schon et al. 2022), with numbers significantly lower in the crop compared to the pasture-baleage wintering treatment.

Pasture recovery

Assessments of pasture cover in the pasture-baleage treatment in 2021 indicated that, on average, 86% of the plots remained bare approximately three months after grazing. Whilst a significant improvement in pasture recovery was noted four months after grazing, about 30% of the area of each plot had no pasture cover, requiring resowing. Pasture recovery following winter grazing in 2022 and 2023 was faster than in 2021 with pasture covering 75% and 90% of the plots three months after grazing for the two years, respectively. Such rapid pasture recovery is supported by Meneer et al. (2005) who showed that the ryegrass component of a pasture can recover from severe pugging in as little as 50 days. This meant that pasture production at the first grazing in spring (dates shown in Table 1; unfortunately, not measured in 2021), was 2900 kg DM/ha in 2022 and 1970 kg DM/ha in 2023. This pasture regrowth was sufficient to result in the uptake of 46 kg N/ha by the time of the first grazing in early October 2022 and 36 kg N/ha at the grazing in September 2023. Plant uptake of N in late winter/ early spring, compared to leaving soil

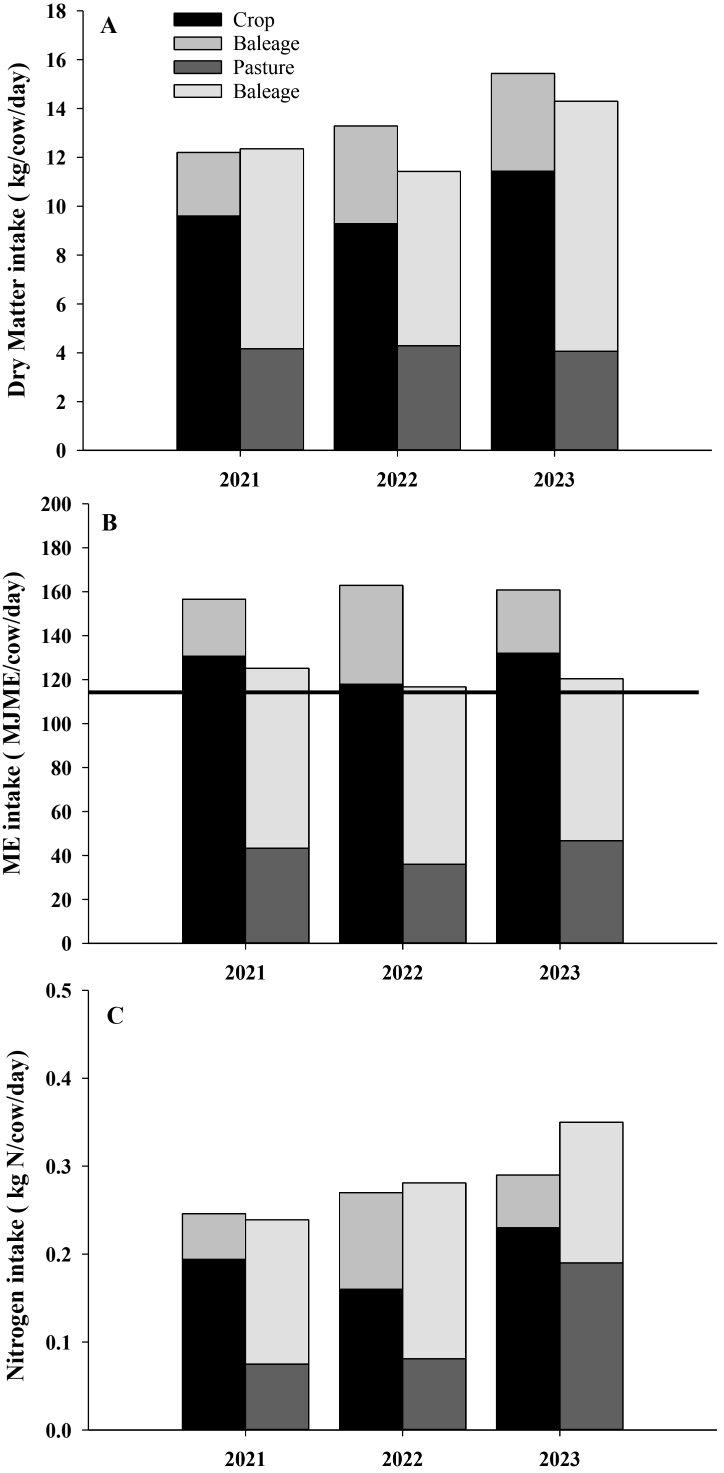

Figure 2 Estimated or measured daily (A) dry matter (kg DM/cow), (B) metabolisable energy (MJ ME/cow/day) and (C) nitrogen (kg N/cow) intakes for cows within the pasture-baleage and crop wintering treatments at the Telford study site. The line in (B) indicates the ME requirements for a 450 kg cow covering maintenance + pregnancy (8 weeks pre calving) and assuming a gain in Body Condition Score of 0.5 (DairyNZ 2021).

Table 3 Soil damage caused by winter grazing as measured by pug depth and % change in surface roughness at the Telford study site. LSD (P<0.05) and P values are also given (bold if significant).

Treatment	Year		
	2021	**2022**	**2023**
Soil Roughness (%)			
Crop wintering	9.7	12.1	10.9
Pasture-baleage wintering	4.7	3.3	5.9
Ungrazed Fenceline	0.7	1.4	1.8
LSD $_{(P<0.05)}$	2.7	2.3	2.7
P value	**<0.001**	**<0.001**	**<0.001**
Pug Depth (cm)			
Crop wintering	14.7	7.8	8.1
Pasture-baleage wintering	12.7	6.8	4.5
LSD $_{(P<0.05)}$	0.9	0.5	0.8
P value	**<0.001**	**0.003**	**<0.001**

Table 4 VSA scores and worms numbers recorded at the Telford study site in October 2022. VSA scores less than 10, 10-20 and >20 indicate poor, moderate or good soil conditions, respectively (Shepherd 2000).

Treatment	VSA score	Worms/m^2
Crop wintering	6.5	57
Pasture-baleage wintering	10.8	244
LSD$_{(P<0.05)}$	3.0	117
P value	**0.007**	**0.011**

bare following winter forage crop grazing, can reduce N leaching, as has been demonstrated by others (Carey et al. 2016, Malcolm et al. 2022).

Leaching losses of N and P

When drainage commenced in 2021, inorganic N concentrations were high (>18 mg/L) with no treatment differences discernible (Figure 3). These high initial concentrations were predominantly in the form of NH_4-N which accounted for 76% of the inorganic N leached that year. This may have been a result of the very wet conditions experienced during the 2021 winter grazing event when a large proportion (64%) of total annual drainage occurred within 10 days of the winter grazing. While these cold (and wet) conditions would likely have slowed the nitrification conversion of NH_4-N to NO_3-N, macropore flow following rainfall events has also been linked to rapid and extensive leaching of urinary-N from structured soils (Shepherd et al. 2014). Concentrations then declined until mid-October (156 mm of cumulative annual drainage) before starting to increase again, particularly in the crop wintering treatment. This increase was likely due to nitrification of the remaining soil NH_4-N as soil temperatures increased (Cookson et al. 2002).

Concentrations of inorganic-N in 2022 were initially low (<5 mg N/L), increasing to a peak of 14 mg N/L before plateauing until 175 mm of cumulative drainage had occurred (mid-November). This elution profile was unexpected. For soils that exhibit preferential flow, N concentrations would be expected to start off high, then rapidly decrease over winter as NO_3-N in the soil profile is removed in mole-pipe drainage (as described in Monaghan et al. 2016). One explanation could be that due to the relatively severe drought of summer and autumn in 2022, the pasture-baleage treatment was not grazed after January (Table 1). This would have resulted in less urinary N deposition and thus less potentially leachable N available to be leached over the ensuing winter. Treatment concentrations of inorganic N in

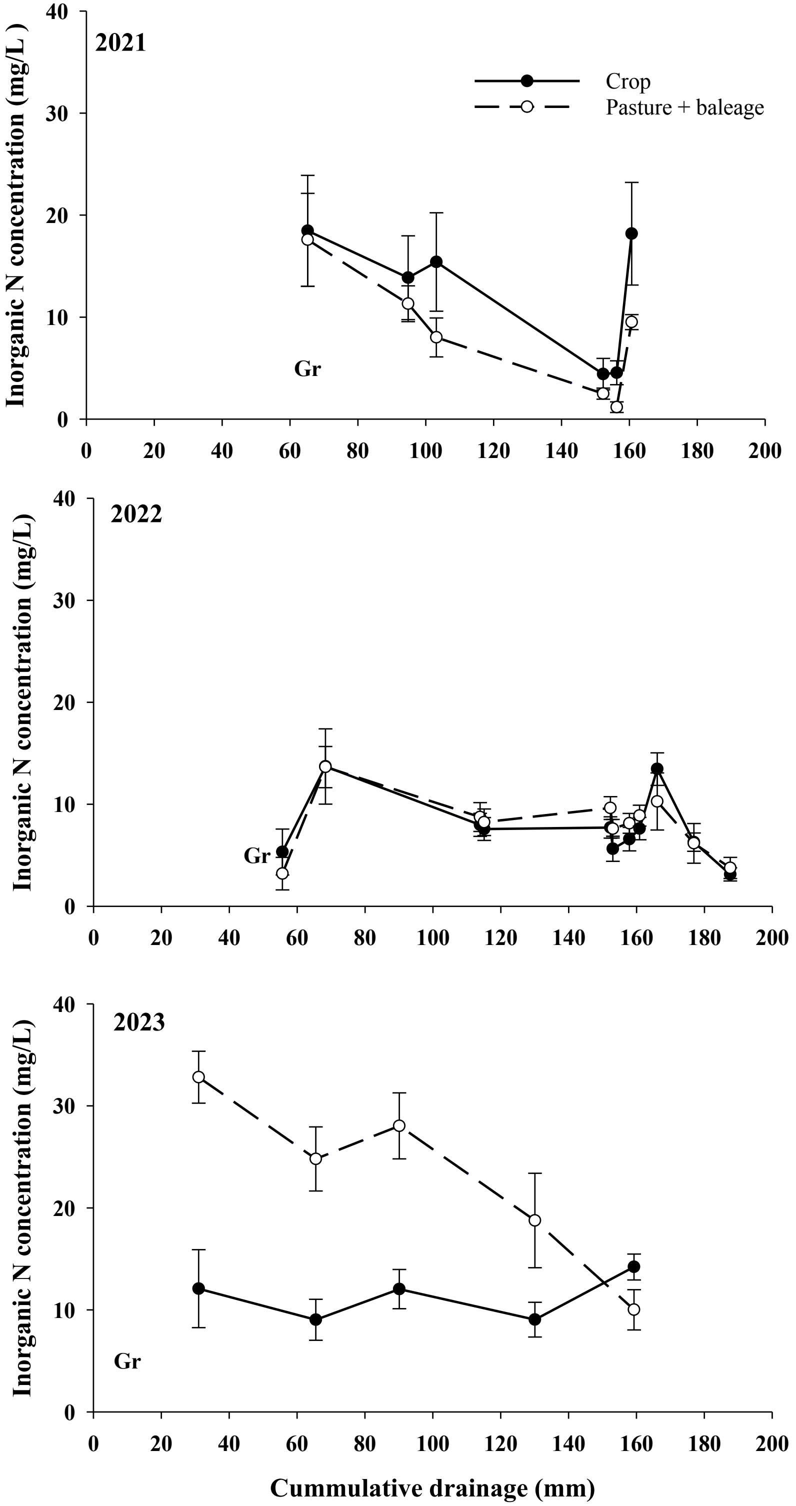

Figure 3 Concentrations of inorganic N (NH_4-N + NO_3-N) in drainage from the crop and pasture-baleage wintering treatments (2021-2023) at the Telford study site. Error bars indicate the 90% confidence intervals. Gr indicates the time of winter grazing.

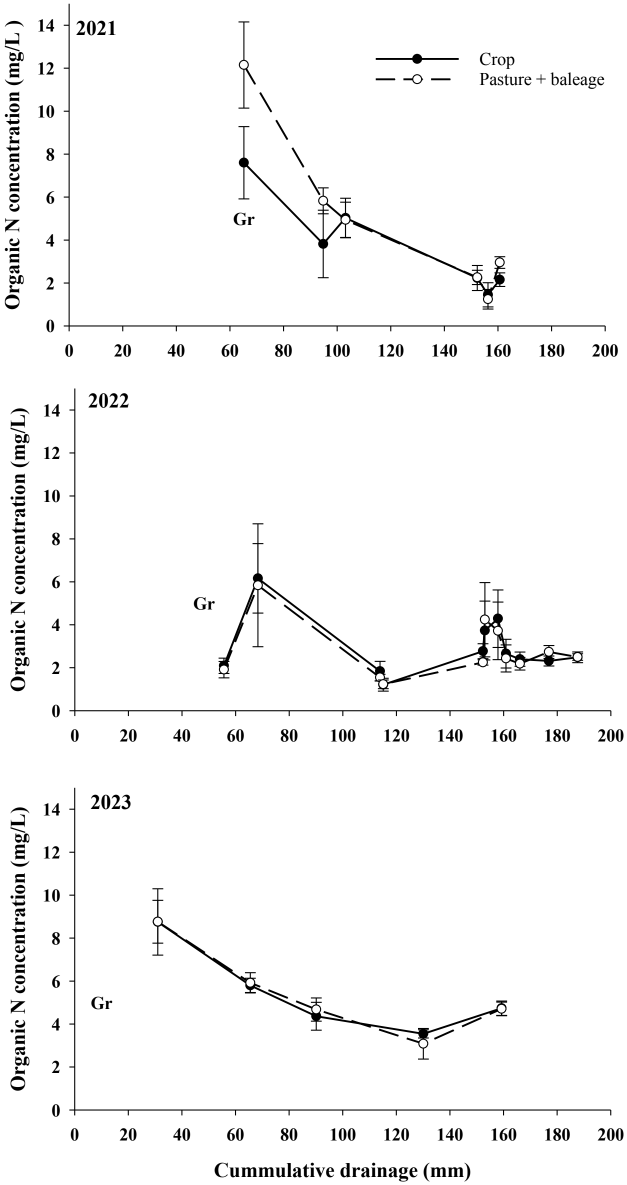

Figure 4 Concentrations of organic N (TON) in drainage from the crop and pasture-baleage wintering treatments (2021-2023) at the Telford study site. Error bars indicate the 90% confidence intervals. Gr indicates the winter grazing.

most drainage events sampled in 2021 and 2022 were very similar. In contrast, inorganic N concentrations in the pasture-baleage wintering treatment were relatively high in 2023, most probably reflecting the effects of urinary N deposition from a late autumn grazing in May 2023 (Table 1) to control pasture quality. Compared to 2021, NO_3-N was the predominant form of N leached in 2022 and 2023 and accounted for 89% and 91% of the inorganic N leached, respectively.

Concentrations of TON in drainage mostly followed a similar pattern for both the crop and pasture-baleage treatments (Figure 4) in that concentrations were initially higher following the winter grazing and declined as the drainage season progressed. There were no differences between the crop and pasture-baleage treatments except in autumn 2021 when the pasture-baleage TON concentrations were significantly higher. The average concentrations of TON measured here (3 – 5 mg/L) are higher than the few values of TON mentioned in the literature for tile drains (0.1 to 1.9

Table 5 N and P losses (kg/ha) in drainage from the pasture-baleage and crop wintering treatments, 2021-2023. LSD ($P<0.05$) and P values also given (bold if significant).

Year	Pasture-baleage wintering	Crop wintering	LSD $_{(P<0.05)}$	P value
2021				
NH_4-N	15.5	11.2	5.7	0.107
NO_3-N	1.8	7.1	6.5	0.092
Inorganic N	17.3	18.2	6.7	0.743
TON	11.3	7.2	3.1	**0.020**
Total N	28.6	25.5	7.3	0.318
FRP	0.037	0.012	0.03	0.127
TDP	0.089	0.034	0.06	0.073
Particulate P	0.159	0.113	0.06	0.107
Total P	0.248	0.147	0.12	0.085
2022				
NH_4-N	1.4	1.3	0.6	0.862
NO_3-N	12.0	11.8	1.9	0.802
Inorganic N	13.4	13.2	1.8	0.743
TON	4.3	4.6	1.3	0.513
Total N	17.7	17.8	2.6	0.927
FRP	0.036	0.032	0.04	0.784
TDP	0.051	0.053	0.04	0.921
Particulate P	0.030	0.051	0.02	**0.018**
Total P	0.081	0.104	0.05	0.333
2023				
NH_4-N	2.1	2.0	1.2	0.874
NO_3-N	34.0	15.6	10.1	**0.004**
Inorganic N	36.0	17.6	9.6	**0.003**
TON	8.5	8.6	0.8	0.830
Total N	44.6	26.2	9.3	0.003
FRP	0.450	0.265	0.256	0.126
TDP	0.558	0.453	0.301	0.426
Particulate P	0.452	0.538	0.152	0.218
Total P	1.011	0.991	0.432	0.915

mg/L; Tanner and Sukias 2011).

Drainage losses of N for the three-year monitoring period are presented in Table 5. No statistically significant differences were found between treatments for 2021 and 2022, but significantly more inorganic N (predominantly nitrate) was lost from the pasture-baleage than the crop wintering treatment in 2023. The N leaching results in Figure 3 and Table 5 show relatively low amounts of inorganic N leaching following winter grazing of crops or pasture. Losses in 2021 and 2022 are particularly low compared to those reported in the literature (e.g. Shepherd et al. 2012; Smith and Monaghan 2020) and most probably reflect the combined effects of relatively low drainage volumes (to displace soil inorganic N) and presumably a high potential for N removal via denitrification due to the severe soil deformation observed in both treatments (Thomas et al. 2019). The drainage and elution curves shown in Figures 1 and 3, respectively, indicate that there was insufficient drainage to displace residual inorganic N left in the soil following winter grazing events in 2021 and 2022. This was particularly evident in 2022, when approximately one-third of annual drainage had already occurred before winter grazing took place. A notable feature of the N leaching response observed in 2023 is the probable effect that a late autumn grazing of the pasture-baleage treatment had on the amount of N potentially available for leaching over the subsequent winter. The decision to make such a late grazing was taken on the basis that (i) some form of harvesting was required to ensure that the annual ryegrass maintained a suitable quality for grazing during winter, and (ii) a late mechanical harvesting would have been logistically difficult and deemed a management artefact that would not occur in typical dairy farming situations.

Total organic N losses were similar for both treatments and accounted for on average 27% (range = 19 to 33%) of total N losses in drainage. This is in line with previous work in Southland which has shown that TON can account for 24% of the total N losses under pasture on a similar Pallic soil type (Tanner and Sukias 2011).

There were no significant differences between the

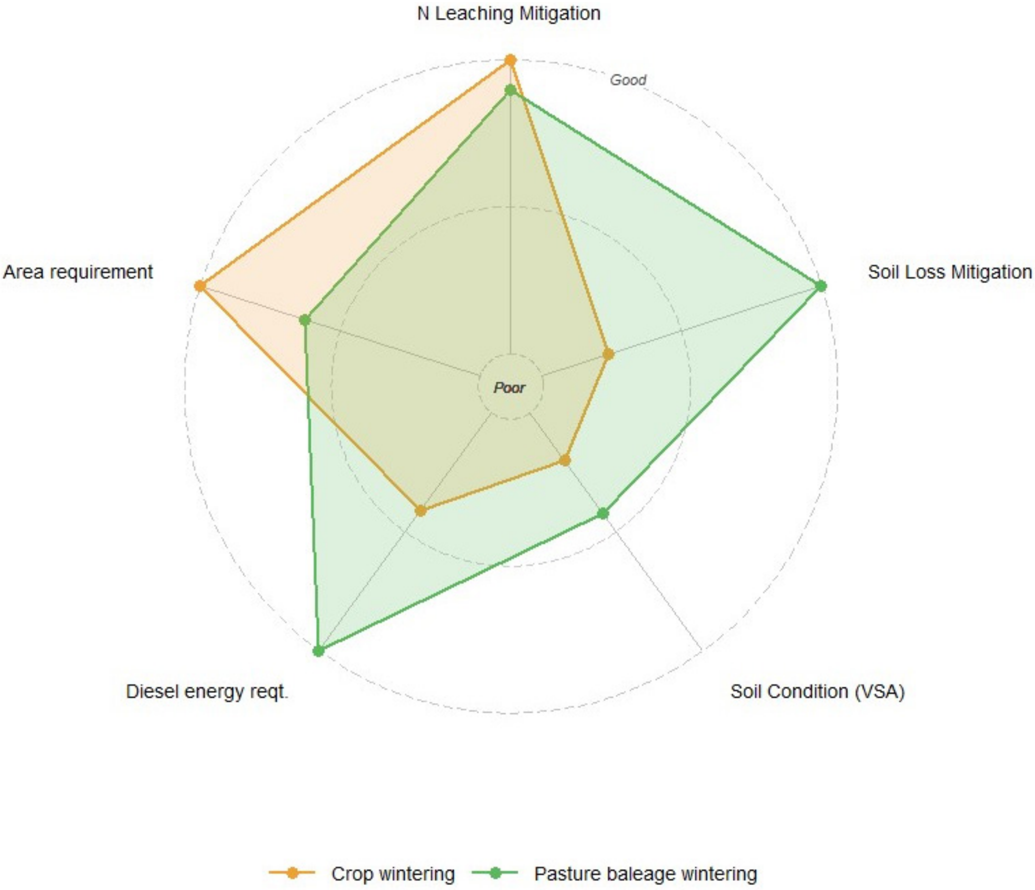

Figure 5 Radar plots of various performance indicators for the pasture-baleage (shown in green) and crop (shown in orange) wintering treatments evaluated at the Telford study site. Favourable outcomes are shown as values located at the outer perimeter of the radar diagram. Indicators for soil condition (2022 VSA results) have been normalised assuming 28 is a favourable score. Remaining results have been normalised against the most favourable outcome measured (N leaching; daily area requirement) or calculated (soil loss; diesel energy use) for each indicator.

two grazing treatments in the amounts of P lost in drainage for 2021 and 2023 (Table 5) although losses were higher in 2023. The crop treatment did however lose more particulate P in 2022 (P=0.018) although these losses were lower than measured in 2021 or 2023. Particulate P accounted for 70% of the P lost in 2021 but only 43 to 49% of that lost in 2022 and 2023. These losses of P are within the ranges reported in literature for mole-pipe drained soils under pasture in Southland (Monaghan et al. 2016) and Waikato (McDowell et al. 2008). Such losses were not unexpected as soil treading damage under wet soil conditions is known to increase the likelihood of P loss, particularly in overland flow (McDowell et al. 2003; Simmonds et al. 2016) but also in subsurface drainage (Monaghan et al. 2016).

System comparison

The pasture-baleage approach to cow wintering delivered fewer benefits to the outcomes that were hypothesised at this study site (Figure 5). The clearest benefit can be seen for estimates of soil loss mitigation, reflecting the modelled effect of greater vegetative cover (areal extent and duration, expressed through the C factor in the Revised Universal Soil Loss Equation (Renard et al. 1997)) compared to that observed and modelled in the crop wintering treatment. Of note in Figure 5 are the low VSA scores of soil condition in both treatments. These reflect the combined effects of relatively high grazing pressures that were imposed (13 - 16 or 10 m^2/cow/day in the pasture-baleage and crop wintering treatments, respectively, equivalent to 0.55 v 0.85 RSU/m^2/day) and the structurally vulnerable nature of the poorly-drained Timaru silt loam soil. Other factors that may have contributed to such poor soil condition were: i) the absence of a comfortable lying surface (such as hay) to encourage cow loafing (and thus minimise trafficking and resulting soil treading damage); and ii) the reduced levels of soil armour/strength that resulted from the decision to use full cultivation to establish annual ryegrass pasture in two of the three years of study. Evidence of soil damage was most apparent in winter 2021 when wet conditions were experienced prior to and during grazing of the treatments. Better soil and pasture conditions were observed for the drier and frosty conditions experienced whilst grazing the treatments in winter 2023. We also note that these visual observations of soil damage tended to more closely align with trends between treatments and years for measurements of pug depth, rather than soil roughness (Table 3). The error terms associated with this indicator were also notably smaller than those for measurements of soil roughness, suggesting pug depth may be a more robust indicator of soil responses to winter grazing effects. Both measures did show consistent treatment responses, however.

Conclusions

The lack of a favourable outcome of pasture baleage wintering compared with crop wintering for mitigating N leaching at this site is a cautionary reminder that treatment responses can differ to those that are hypothesised, due to unanticipated soil and management effects. The relatively low concentrations of N in drainage from both treatments combined with the poor soil conditions observed at the site suggest that there may have been much N removal via soil denitrification, a process that is very poorly quantified in New Zealand soils. Our results also illustrate the challenges of modelling N leaching from landscapes where both the amount and temporal pattern of surplus rainfall inputs can have a large influence on the potential for N transport in drainage. The poor soil conditions observed in the pasture-baleage treatment suggest that this wintering approach offers only modest advantages to soil and water quality when deployed on structurally vulnerable soils. Other measures to help minimise soil treading damage are likely needed to improve outcomes on such landscapes.

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