An analysis of winter/early spring application of synthetic nitrogen fertiliser in grazed pasture-based systems in New Zealand

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April 2023

Report for The Fertiliser Association of New Zealand

Client Report Number RE450/2023/015

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Contents

1. Executive Summary

- The strategic use of nitrogen (N) fertiliser is integral to maintaining the economic viability of New Zealand (NZ) dairy pasture systems.

- The use of N fertiliser in farming, however, is under increasing scrutiny in NZ due to its reported direct and indirect effects on water quality (from nitrate leaching) and on concentrations of greenhouse gases (from nitrous oxide emission).

- The Fertiliser Association of New Zealand (FANZ) wish to understand the potential impact of a possible ban on winter (May-July) applications of N fertiliser on dairy farm systems.

- This report reviews a wide range of available scientific evidence with respect to the impact of winter/early spring nitrogen fertiliser application in grazed pasture systems, under different conditions, across different areas of NZ.

- Key findings of this review are:

    - Available evidence indicates that direct leaching of N from fertiliser in grazed pasture systems is generally low (< 10% of N fertiliser applied) if application rates are not excessive (i.e., < 200 kg N ha^{-1} yr^{-1}) and are synchronised with periods when pastures require N and is actively growing.
    - There has been some limited research in New Zealand investigating the effect of timing (season) of N fertiliser application on N volatilisation from pasture, and with mixed results.
    - Winter nitrous oxide (N_2O) emission factor (EF) (N_2O-N emitted as a % of N applied) is reported to be highest of all seasons.
    - In practice, a feed shortage in early spring is probably best met by N application sufficiently late winter that the nitrogen response rate has risen from the winter lows rather than in autumn or early winter. At this time, plant uptake is more rapid, losses are likely to be least, and the pasture response is likely to be higher.

- The review is further supplemented by scenario modelling using The Agricultural Production Systems sIMulator (APSIM).
    - The scenarios were decided in collaboration with FANZ.
    - Simulations were done without (Baseline) and with (No-Winter) a ban on winter N applications. For pairs of Baseline and No-Winter simulations, total N fertiliser inputs and milk solids production were kept constant meaning that no intensification was permitted within the simulation. The fertiliser scenarios were of timing of applications rather than the total amount of N applied. Milk solids production was maintained by manipulating supplementary silage feeding.
    - Additional simulations of the nitrogen response rate (NRR) as affected by soil, climate and month of application were done to assist interpretation of the main simulations.

- Examining of the baseline simulation results suggests that the model outputs are reasonable given the simulation and farm system rules imposed.
    - Moving fertiliser applications away from winter (May-July) towards the prior autumn or following spring also meant that the applications were at a time of year when NRR was higher than in the Baseline winter applications.
    - The No-Winter scenario resulted in minimally changed simulation outputs – none were statistically or practically significant. Simulated leaching was similarly unaffected.
    - These simulations do not include overland flow processes. Therefore, this study cannot determine if moving fertiliser applications away from winter, when runoff events are more likely, would reduce N losses by surface flow mechanisms.
    - The scenario rules prevented the farm intensification (i.e., an increase in milk production) that might otherwise result from moving N applications from winter to a time of year when NRR is higher. If such intensification occurred, then leaching may also increase.

- The review and modelling suggest that, provided a no-winter N fertiliser policy is not accompanied by increased farm intensification, the effects on-farm are likely to be minimal.

2. Introduction

Nitrogen (N) is an essential plant nutrient required for the growth of grass/clover pasture (Hay and Porter 2006). Historically, grazed ryegrass (*Lolium perenne* L.)/white clover (*Trifolium repens* L.) based pasture systems in New Zealand have relied on N supplied from symbiotic N fixation from white clover to support their productive potential (Walker and Ludecke 1982; Syers 1982). However, research has established that even well managed grass/clover pastures remain deficient in N for much of the year and respond to the application of N fertiliser (Steel 1982; Carran 1978; Field and Ball 1978). As a result, synthetic N fertiliser use has increased significantly over the last 30 years, particularly in dairy systems (StatsNZ 2021), and is now widely used to ensure high productivity of grazed pasture (Figure 1).

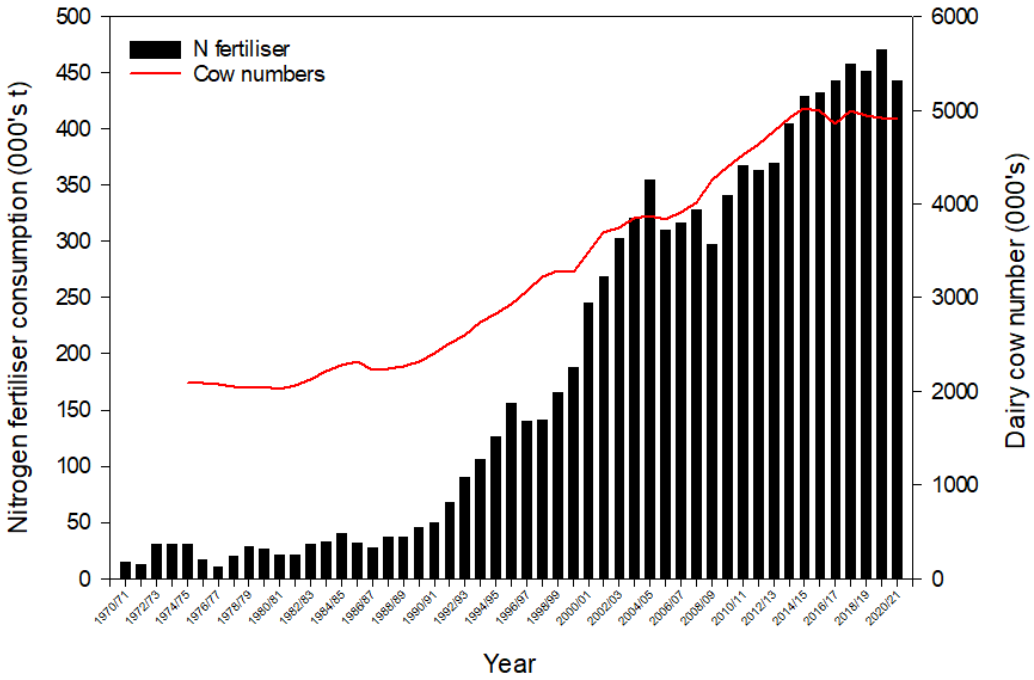

Figure 1. Nitrogen (N) fertiliser consumption in New Zealand between 1970 to 2021 (sourced from Rogers and Little (1982) and the Fertiliser Association of New Zealand) and cow numbers between 1974 to 2021 (sourced from Livestock Improvement Corporation Limited).

Initially, in dairy systems, N fertiliser was used mainly to enhance the establishment of new pasture (Catto and Roberts 2021). However, supported by research undertaken in the 1970's, there was a shift towards using N fertiliser more strategically, to enhance pasture growth rates during periods of year when there was a feed deficiency for grazing animals (Roberts et al. 1992) or where growth response was the greatest, with feed conserved until required (Beukes et al. 2017). Feed deficiencies typically occur in winter/early spring and summer, when soil fertility is sub-optimal due to wet and cold or dry soil conditions respectively, that restrict the ability of soil biological and chemical processes to keep essential nutrients such as N cycling in soils and plants growing. More recently, the pattern of N fertiliser use on dairy farms has changed again, with N often being applied all year-round, following the cows' grazing rotation (Chapman et al. 2018). In sheep and beef systems, N use has also increased (StatsNZ 2021), albeit slower due to lower pasture response to N (kg of DM kg^{-1} N). Total inputs on sheep and beef farms are relatively low at around 14 kg N ha-1 yr^{-1} for a whole-farm New Zealand average (Beef + Lamb New Zealand 2020). On these farms, N fertiliser use has predominantly targeted crop and specialty areas of the farm, although increasingly it is also being used in autumn and spring to fill feed deficits (Catto and Roberts 2021; Lambert et al. 2012).

The use of N fertiliser in farming, however, is under increasing scrutiny in New Zealand due to its reported direct and indirect effects on water quality (from nitrate leaching) and on concentrations of greenhouse gases (from nitrous oxide emission). In response, regulation has been introduced to mitigate the adverse effects of N fertiliser use in pasture systems (e.g., cap on rate of synthetic N fertiliser) on water quality, and other regulations are being considered. One possible regulation of particular concern to FANZ is the control on winter/early spring application (e.g., with arbitrary cut-offs, 30 May to 30 September) of synthetic N fertiliser. This would presumably be in response to the recognition that soil conditions (temperature and moisture) may be sub-optimal during winter/early spring for N uptake in pasture in parts of New Zealand, increasing the risk of N loss. However, with the large geographic and climatic variation across New Zealand, a rigid nationwide seasonal control on N use may not be the most appropriate approach, as it is likely there are regions of New Zealand where winter/early spring N fertiliser use is still agronomically and economically viable with only limited environmental risk.

A range of studies have previously investigated the effects of winter applied N fertiliser to pasture on N response rates and N loss from soils. Although only a limited number of studies have been undertaken in New Zealand (e.g., Ledgard et al. 1988; Korte 1988; Feyter et al. 1985; Sherlock and O'Connor 1973; Hoglund 1980), research undertaken in south Australia and Tasmania may be relevant to some New Zealand pasture systems (e.g., Christie et al.2018; Eckard and Franks 1998). However, there has not been a systematic review of this previous research and discussion of the implications of controls of winter/early spring N use in pasture systems in terms of the impacts and trade-offs on the environment, forage supply, productivity, and animal welfare.

The expected benefit of a science-based review of the control of winter/early spring N use in pasture systems would however better position FANZ to provide advice and inform any future debate in relation to the judicious use of N fertiliser following industry guidelines, and ensure controls are science based, necessary and appropriate to achieve the required outcomes, while recognising the trade-offs incurred.

The aim of this report is to present a science-based review of the implications of the use or exclusion of winter/early spring N fertiliser (30 May to 31 July) in pasture-based systems in terms of the potential impacts and trade-offs on the environment, forage supply, productivity and animal welfare. This study will provide an assessment of published and expert evidence on the impact of winter/early spring N application under different conditions grazed pasture systems across different areas of New Zealand.

It will focus on:

- Conditions when winter/early spring N fertiliser might be considered or alternatively excluded
- Relative contribution of winter/early spring N fertiliser use to the N cycle and overall annual farm system N loss
- Impact on the environment, forage supply and animal welfare

The review was supplemented by scenario modelling. The Agricultural Production Systems sIMulator (APSIM) was used to investigate the effects on a farm system of moving N applications away from winter (to autumn or spring) for a range of soils and climates.

This document is structured as follows:

- The impact of winter/early spring N fertiliser application on environment is presented in Section 3.
- Impact of a change in N fertiliser policy on animal welfare is described in Section 4.
- APSIM modelling results are presented in Section 5.

3. Impact of winter/early spring nitrogen fertiliser application

3.1. Plant uptake of N

Ledgard et al. (1988) investigated the effect of winter temperature i.e. mild (11°C days and 7°C nights) or cold (varying down to 6°C and 1°C nights) and time of N application i.e. early or late winter application of ^{15}N labelled fertiliser to a grass/clover pasture. In all treatments plant uptake of applied N was rapid and virtually complete by the first harvest one month after application, with 72–77% of the added N taken up by plants (Table 1). The remaining N was found predominantly in the microbial biomass. There was no effect of temperature on N uptake in this study, with most of the applied N found in plant roots, and then transferred from roots to shoots in subsequent harvests.

Table 1. Plant uptake of 15N-enriched ammonium sulphate (as a % of total applied) as influenced by time of application and winter temperature regime.

		Early winter application			Late winter application		
Harvest no.	Plant part	mild	cold	SED	mild	cold	SED
1	Shoots	19.5	17.4	2.2			
	Roots*	53.1	53.1	3.0			
2	Shoots	18.9	20.9	2.8	36.0	33.9	3.4
	Roots	ND	ND		43.7	50.2	4.0
3	Shoots	7.8	9.8	0.8	11.0	13.1	1.5
	Roots	30.7	25.5	3.0	26.3	25.3	2.5
Total plant uptake		76.9	73.6		73.3	72.3	

ND = not determined; *Includes stubble below 10 mm from soil surface

3.2. Forage supply

The early findings by Lynch (1953) and During and Weeda (1968) of enhanced pasture response from late winter/early spring applications of N fertiliser were the catalyst for a large body of subsequent research in New Zealand that investigated whether N fertiliser could be used as a reliable management tool to offset seasonal N deficiency in grass/clover pasture (O'Connor and Gregg 1971).

Between 1969 and 1974 a series of national field trials were established to examine the response rates of N fertiliser and the effect of time of application on mixed grass-clover pasture productivity (O'Connor 1982). In brief, 405 experiments were conducted over a six-year period at a series of lowland sites. Each experiment consisted of four rates of lime ammonium nitrate (now termed calcium ammonium nitrate) equivalent to 0, 25, 50 and 100 kg of N ha^{-1}, replicated six times. The results of the trials confirmed significant pasture responses to N fertiliser applied in winter/spring (June to October), which were generally higher and more reliable than N applied in late summer/autumn (Feb to May). For instance, for winter/spring N fertiliser application (25 kg N ha^{-1}), the average pasture response (over three months) ranged from 3.6 to 24.1 kg DM kg^{-1} N (mean 13.1 kg DM kg^{-1} N). For autumn N applications, the average pasture response ranged from 2.8 to 20.0 kg DM kg^{-1} N (mean 7.0 kg DM kg^{-1} N).

Numerous studies undertaken since the national trial series on both lowland and hill country sites across New Zealand have confirmed the finding of the N trials (e.g. Hoogendorn et al. 2017; Puha et al. 2008; Gillingham et al. 2008; 2007; 2003; Smith et al. 2000; Roberts and Thomson 1989; Parker et al. 1989; Ball and Field 1982; Steele et al. 1981; Ball et al. 1982; Luscombe 1979, 1980; Harris et al. 1973; Holmes and Wheeler 1973). Feyter et al. (1985) for example measured pasture production in five harvests in consecutive months from March to August over two years after the application of N fertiliser (0, 25, 50, 100 kg ha^{-1}). Pasture response to N fertiliser in harvest one was greatest from the August application, although good responses were found across all winter applications (Table 2).

Table 2. Total responses (kg DM ha-1) to nitrogen (N) applied in March to August. Values in brackets show efficiency of the N applied (kg DM kg-1 N) (adapted from Feyter et al. 1985)

Month of application	N applied (kg ha^{-1})					
	25		50		100	
March	131	(5.2)	326	(6.5)	503	(5.0)
April	256	(10.2)	244	(4.9)	400	(4.0)
May	111	(4.4)	211	(4.2)	258	(2.6)
June	292	(11.7)	514	(10.3)	858	(8.6)
July	220	(8.8)	501	(10.0)	830	(8.3)
August	393	(15.7)	635	(12.7)	959	(9.6)

Ledgard et al. (1988) measured the response of grass/clover pasture to 50 kg N ha^{-1} of urea (^{15}N labelled) applied in May, June, or August.. In all instances, applied N increased pasture growth during the first two or three harvests. There was a subsequent reduction in pasture growth which lasted for 2-3 harvests. The efficiency of N use at the first harvest was 4.6, 6.2, and 6.2 kg DM kg^{-1} N for May, June, and August applications respectively with residual responses of 1.8, 2.6 and 4.9 kg DM kg^{-1} N respectively. Uptake of ^{15}N-labelled fertiliser was most rapid after the August N application but was slow and prolonged after the May N application. A similar finding was reported by Cookson et al. (2001), where the plant uptake of late winter applied ^{15}N-labelled fertiliser was almost twice (33.3%) that of autumn applied N fertiliser (18.8%) and resulted in a significantly greater plant yield.

Sherlock and O'Connor (1973) measured the pasture response to N fertiliser (25, 50, 100 kg N ha^{-1}) applied monthly between April and October at a hill country trial in Te Kuiti. They found the best percentage and total DM responses were obtained from early late winter/spring applications of N, particularly August, with no response to N applied in June (Figure 2).

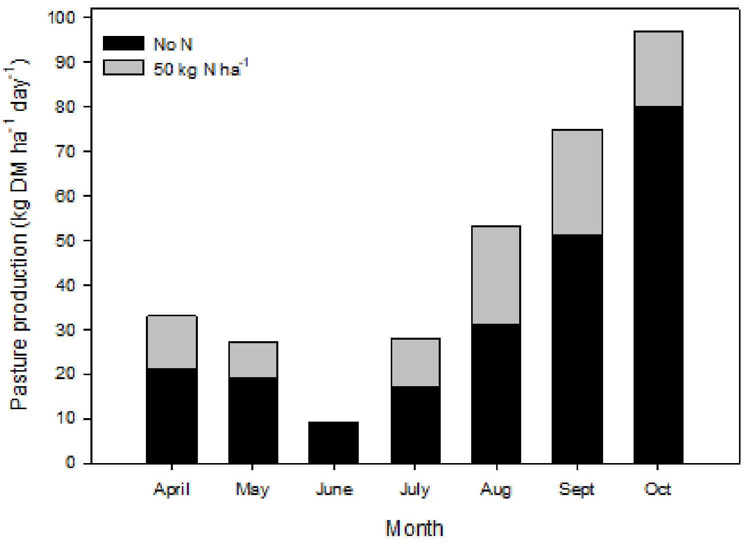

Figure 2. Pasture production from the application of nitrogen (N) fertiliser applied over the April to October (adapted from Sherlock and O'Connor 1973).

Table 3. Dry matter (DM) accumulation and nitrogen (N) use efficiency over six weeks regrowth following the application of two rates of N fertiliser applied between May and September (adapted from Ball and Field 1982).

	45 kg N ha^{-1}		180 kg N ha^{-1}	
Date N applied	DM accumulation (kg ha^{-1})	Efficiency (kg DM kg^{-1} N applied)	DM accumulation (kg ha^{-1})	Efficiency (kg DM kg^{-1} N applied)
13 May	920	5.0	1350	2.8
11 June	650	5.5	860	2.4
7 July	1040	7.3	1470	4.7
8 August	2950	32.9	4930	19.1
2 September	2900	10.0	4330	10.4
30 September	3220	7.9	3700	4.7

Korte (1988) found average response rates for N fertiliser (25, 50, 100 kg N ha^{-1}) applied to five East Coast Hill country farms in Gisborne-East (North Island) varied four-fold depending on the month of fertiliser application. Responses to N fertiliser measured were in general similar to those recorded in other regions. Response rates were 6.7, 8.6, 3.8, 12.0, 12.3, 11.6 and 8.5 kg DM kg^{-1} N from N fertiliser applied in March, April, May, June, July, August and September, respectively.

The reason pasture responds well to N fertiliser applied in winter/early spring is because plants are N deficient. From late autumn through winter, lower soil temperatures restrict clover growth and soil microbial activity, resulting in lower N fixation and soil N mineralisation, and often there is some N loss *via* leaching. This means there is less N available in the soil for plant uptake (O'Connor 1982; Field and Ball 1978; Mitchell and Lucanus 1962). Research also shows that plant uptake of N uptake is temperature-sensitive, and N uptake only readily occurs once the soil temperature exceeds about 4°C (Hoglund, 1980). For example, a trial in Kirwee in Canterbury, Hoglund (1980) showed that despite repeated applications of N fertiliser from mid-June onwards, there was no growth response until 15 August (Figure 3). This suggested that, during late winter/early spring, N demand is high and uptake of applied N is rapid once the soil temperature increases to >4.5◦C (Ledgard et al. 1988; Castle et al. 1999), meaning a lower risk of both N removal through immobilisation and/or N losses.

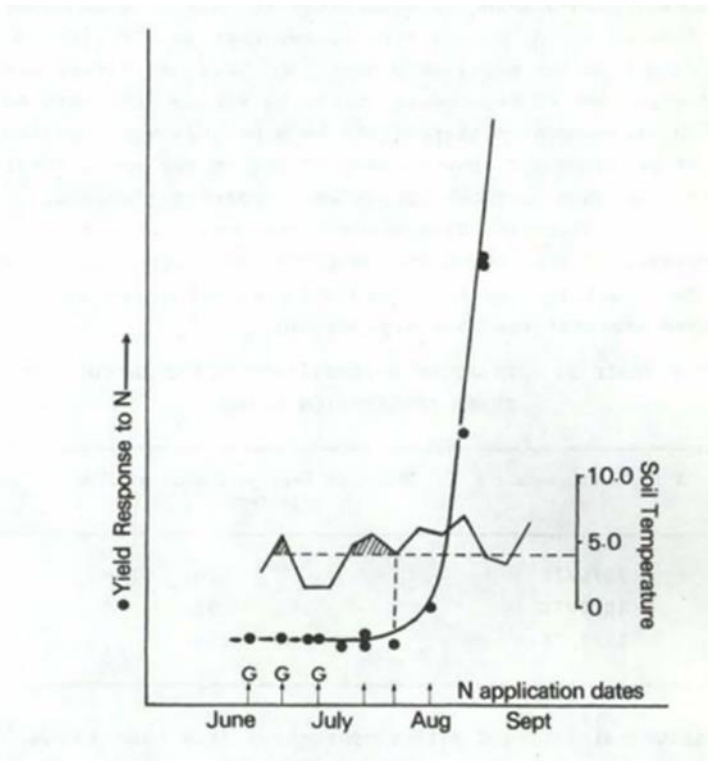

Figure 3. Effect of soil temperature (9 am, 100 mm soil depth) on pasture response to nitrogen fertiliser (from Hoglund 1980).

In contrast, the poorer response in late summer/autumn is due to limited soil moisture, and also higher soil mineral N concentrations and a higher proportion of clover supplying N to the pasture (Keeney and Gregg 1982; Ball and Field 1982; O'Connor

1982). The findings of this research confirms that the application of N fertiliser could be used as a management tool for manipulating seasonal pasture growth.

Roberts et al. (1992) for example investigated the effect of strategic N fertiliser application on pasture growth in a three-year trial in South Taranaki. N fertiliser (40 kg of N ha^{-1}) applied in July/ August could help increase pasture growth to bridge a late winter/early feed deficit, and N applied (60 kg N ha^{-1}) in September/October, could help maximise the amount of pasture production during spring, some of which could then be conserved and fed back to animals over the late summer/autumn period (Figure 4).

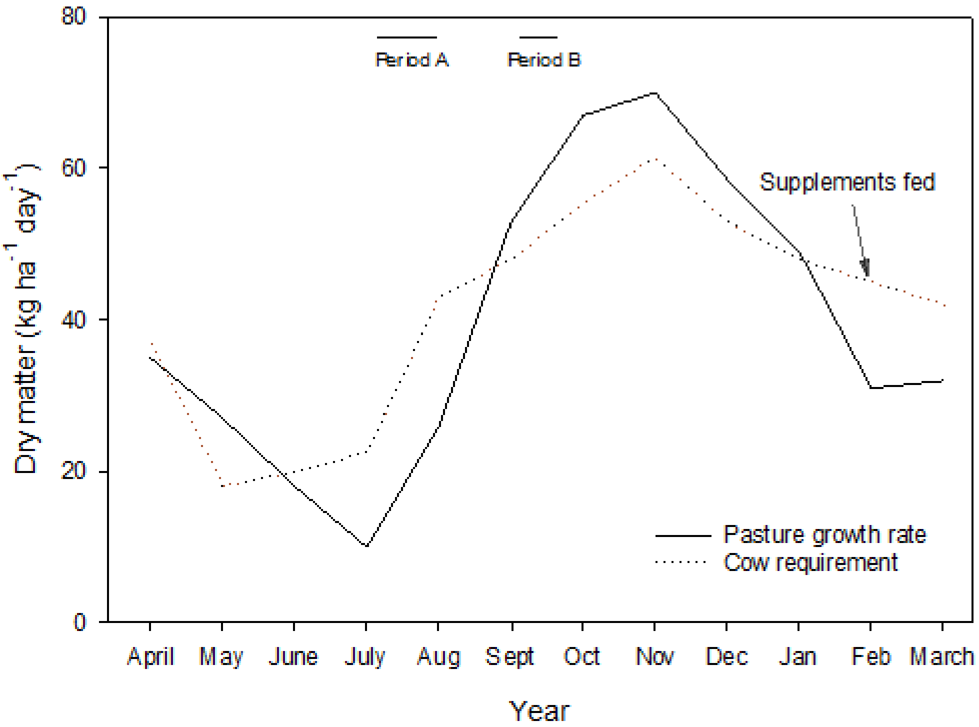

Figure 4. Pasture dry matter production and cow feed requirements and timing of strategic application of nitrogen (N) fertiliser at a trial site in south Taranaki (adapted from Roberts et al. 1992).

In practice, if N is used to address a feed shortage in early spring, it is probably best met by N application in late winter rather than in autumn or early winter. At this time, plant uptake is more rapid and losses are likely to be least. Also temporary immobilisation by the soil microbial biomass will further reduce losses of applied N and can provide a relatively large residual pasture response.

Note that here, by 'late winter' we mean once soil temperatures have increased sufficiently to increase potential pasture growth and the balance between evaporation and rainfall is such that the risk of loss by leaching has substantially reduced. The calendar timing will vary from region to region but also by year within region. Tools to assist farmers in this decision may be useful.

3.3. Environmental effects of winter/early spring N application

One of the big concerns of using of N fertiliser in grazed grass/clover pasture systems is losses to water and the atmosphere. Mineral-N derived from the application of N fertiliser can be lost directly or indirectly *via* i) nitrate (NO_3^-) leaching, ii) ammonia (NH_3) volatilisation and iii) denitrification (i.e. transformations of N into gaseous forms such as nitrous oxide (N_2O) and di-nitrogen (N_2)) (Figure 5).

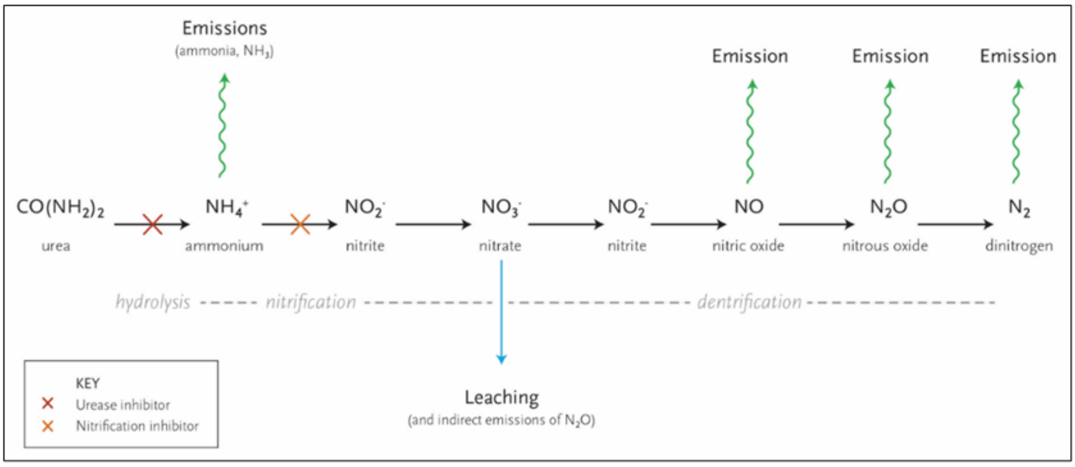

Figure 5. Nitrogen transformation and losses from soil (adapted from Cardenas et al. 2019).

3.3.1. Leaching

The use of N fertiliser increases the potential for N losses *via* NO_3- leaching from soil into water, which is both a loss of plant available N from soil, but also a threat to the environment and human health. As a result, there has been a lot of research over the last four decades in New Zealand that has measured and modelled NO_3-leaching losses from intensively grazed pasture systems and identified the soil and environmental factors and management practices affecting leaching loss (Vogeler et al. 2016; Selbie et al. 2015; Watkins and Shepherd 2015; Monaghan and de Klein 2014; Cameron et al. 2013; Monaghan et al. 2007; Di and Cameron 2002; Ledgard et al. 2001).

While the amount of fertiliser N applied to pasture affects the amount of N leaching, research has established that it is the N excreted by animals, particularly urine, in intensively grazed pasture systems that is the main factor affecting losses (Monaghan et al. 2005; Ledgard et al. 2000, Selbie et al. 2015). Further, even when no N fertiliser is applied, there will still be N leaching loss due to animal urinary excretion from the surplus protein in forage that grazing animals consume (Ledgard et al. 1999; 2000).

The direct leaching of N from fertiliser in grazed pasture systems has been found to be is low (< 10% of N fertiliser applied) if application rates are not excessive (i.e. < 200 kg N ha^{-1} yr^{-1}) and are synchronised with periods when pasture require N and they are actively growing (Monaghan et al. 2005; Cookson et al. 2000; Di and Cameron 2002; Di et al. 1998; Silva et al. 1999; Ledgard et al. 2000).

However, larger N leaching losses from the application of N fertiliser have been reported. Ledgard et al. (1988) measured the amount of inorganic ^{15}N with depth down the soil profile in a pasture soil after it had received ^{15}N labelled urea (50 kg N ha^{-1}) in May, June and August. It was found that total recovery of added ^{15}N was less than 80% for May and June applications but was complete (99%) for the August application. Leaching was reported to be the most likely cause of N loss from N applications in May and June.

3.3.2. Volatilisation

Ammonia volatilisation is the loss of gaseous ammonia (NH_3) to the atmosphere and can occur whenever there is free NH_3 at the soil surface (Bolan et al. 2004). This may be from the application of animal urine and faeces, the mineralisation of soil organic matter and plant residues, as well as from the application of N fertiliser such as urea (Cameron et al. 2013). There has been a large amount of research undertaken in New Zealand investigating NH_3 loss from N fertilisers applied to grazed pasture. This has included quantifying losses, the factors which affect losses, along with the testing of management strategies and technologies to mitigate NH_3 losses. Although losses of N due to NH_3 volatilisation vary, they are typically c. <15% of the N applied from a single moderate application of urea (<40 kg N ha^{-1}). However, greater losses (e.g. 30%) have been reported at higher urea application rates.

There has also been some limited research in New Zealand investigating the effect of timing (season) of N fertiliser application on N volatilisation from pasture with mixed results. Black et al. (1985) found the percentage of urea N applied in September (30 kg N ha^{-1}) lost by volatilisation was slightly lower than losses than N applied at other times of the year (Table 4).

Table 4. Total percentage loss of ammonia (NH3) by volatilisation following broadcast application of nitrogen fertiliser at 30 kg N ha-1. (adapted from Black et al. 1985). DAP = diammonium phosphate; AS = ammonia sulphate; CAN = calcium ammonium nitrate.

	NH_3-N loss			
Application date	Urea	DAP	AS	CAN
3 August 1983	11.2 (0.7)	3.1 (0.6)	0.6 (0.5)	0.2 (0.1)
5 September	7.4 (0.8)	2.2 (0.3)	0.2 (0.1)	-
26 January 1984	13.4 (1.1)	8.2 (0.5)	-	-
9 April	15.0 (1.9)	5.8 (0.7)	1.3 (0.1)	1.0 (0.1)
3 September	12.6 (1.6)	7.0 (0.3)	2.1 (0.3)	1.1 (0.3)

In other experiments, Black et al. (1985) found NH_3 losses from urea were highest during the late autumn/mid-winter months i.e. 17.5% (6 May 1983), 16.9 (17 June

1983), 20.2% (11 June 1984), and 9.6% (6 August 1984). It was concluded, although soil temperature influences several stages of the volatilisation process (Freney et al. 1983), the seasonal temperature patterns were not related to the variations in the percentage of applied urea lost by volatilisation in their studies.

In comparison, Theobald and Ball (1984) found significantly greater losses from N fertiliser applied in early April (Autumn) than in mid-August (Spring) (Table 5). It was speculated by Black et al. (1985) the higher autumn losses may have resulted from the low soil moisture content at the time of urea application (59% of field capacity), that restricted the diffusion of urea away from the granule, thus reducing the soil volume retaining NH_3. This would concentrate urea over a smaller surface, and augment the pH increase required for ammonium will be converted to ammonia gas (Bolan et al. 2004).

Cookson et al. (2001) measured the fate of autumn, late-winter and spring-applied ^{15}N-labelled fertiliser to a ryegrass seed crop over two years. It was reported volatilisation losses in 1996 and 1997 significantly increased with increasing N fertiliser application rate but tended to be higher in the spring (13%) than in the autumn (6%) and winter (7%) seasons.

Table 5. Ammonia volatilisation as a percentage of the nitrogen fertiliser applied to mixed pasture (adapted from Theobald and Ball 1984).

	Ammonium sulphate (50 kg N ha^{-1})	Urea (50 kg N ha^{-1})	Ammonium sulphate (200 kg N ha^{-1})	Urea (200 kg N ha^{-1})
Spring	<0.5	5	<0.5	16
Autumn	8	42	10	86

3.3.3. N_2O emission

Nitrous oxide (N_2O) represents a significant loss of N from the soil/plant because it is a potent greenhouse gas (GHG) and a contributor to stratospheric ozone depletion (Sutton et al. 2014). Most of the N_2O lost from soil is produced biologically, mainly due to the processes of nitrification and denitrification (Cameron et al. 2013; de Klein and van Logtestijn 1994) (Figure 5). Nitrification results in the accumulation of NO_3^- in soil, which is the substrate for denitrification and production of N_2O (McLaren and Cameron 1996).

Emissions of N_2O are controlled by interactions between different soil physical and chemical properties, soil microbiological populations, climate, and animal management practices (Whitehead and Edwards 2015). A focus of research in New Zealand has been calculating N_2O emissions factors (EF) (N_2O-N emitted as a % of N applied) from pasture soils under different conditions (e.g. climate, soils etc.), rate of N fertiliser application and for different types of N including urea (de Klein et al. 2004; Luo et al. 2007, 2010; Kelliher et al. 2014; van der Weerden et al. 2016b) and non-urea fertilisers including ammonium phosphate, ammonium sulphate, potassium nitrate and diammonium phosphate (Zaman et al. 2008; Bhandral et al. 2007).

van der Weerden et al. (2016a) have also reported on seasonal differences in N_2O lost as a percentage of N fertiliser (urea) applied. Analysis of 196 replicate-level EF values that were measured in either autumn (42), winter (49), spring (88) and summer (17), revealed there was a non-significant (P = 0.078) seasonal effect on EF (Table 6). However, the numerical differences in EF between seasons were large, with the overall mean summer value of 0.07%, which was the lowest of all seasons, 18 times lower than the winter value of 1.27% (Table 6).

Table 6. Seasonal EF values (%) for urea (mean; 95% confidence interval) (adapted from van der Weerden et al. (2016a).

Season	Mean	Lower	Upper
Summer	0.07	-0.69	1.50
Autumn	0.18	-0.61	1.66
Winter	1.27	0.17	3.31
Spring	0.46	-0.42	2.08

It was suggested the higher winter EF values may be due to generally wetter soil conditions. In poorly drained soils or in any situation where anaerobic conditions exist, biological denitrification is possible (McLaren and Cameron 1996). Interestingly, summer produced the lowest EF values even though the generally warmer conditions could be expected to stimulate microbial activity, leading to increased N_2O emissions. It was also found that the low summer EF value contrasts with the high EF values reported for urine for the same season (van der Weerden et al. 2016a). It was suggested this may have been influenced by N load, which averaged 53 kg N ha^{-1} for urea. Low N load may lead to increased N use efficiency by actively growing pasture, and therefore lower N_2O emissions, compared to high excreta N loads (average of 612 kg N ha^{-1}).

4. Animal Welfare

Any impact of a change in N fertiliser policy on animal welfare would be *via* feed shortages on farm. Nitrogen fertiliser is used by some farmers to fill feed gaps when animal demand for pasture is greater than supply. A change in farm management, e.g., making and feeding more supplements or forage crops, may be needed to address those regular feed gaps that are expected and so can be planned for in advance. There are also unplanned feed gaps due to unseasonal or extreme conditions and these can emerge quickly at any time of the year (e.g., flooding, unusually prolonged dry conditions). Nitrogen is a slow-response method (e.g., compared to supplementary feeding) to fill feed shortages. This is particularly so at any time when growth is primarily limited by factors other than N supply such as winter when temperatures and radiation limit the pasture response to N. Given this, and that farmers are well-versed in managing their farms under changing conditions, a flow-on effect of preventing winter N applications on animal welfare is unlikely. It may mean that additional supplement reserves are needed and/or greater attention to feed planning.

5. APSIM Modelling

To supplement the existing evidence, the simulation model APSIM was used to simulate a grazed (i.e., including urine patches) paddock within a whole farm under a variety of soil and climate conditions. Simulations were done with and without a ban on winter N applications. The scenarios (soil, climate, timing and amount of fertiliser applications) were decided in collaboration with FANZ and resulted in four regions, each with four combinations of contrasting soil and climate conditions. The methods and datasets used to set up the APSIM model are presented in Appendix A. Briefly, sixteen scenarios were simulated. In each of four regions (Northland, Waikato, Canterbury, Southland), two climates and two soils were selected for simulation.

The key outputs from the simulations used in this report were:

- pasture grazed;
- number and timing of grazing events;
- silage fed;
- number of silage feeding events;
- silage made; and
- nitrogen leached.

These values were output from the simulation at each grazing event and, where necessary, accumulated the outputs from the previous grazing event. After discarding the initial three years of outputs the data was summarised into annual values. A calendar year was used for simplicity of analysis.

5.1. Results and discussion

The sections below describe the outputs from the Baseline scenarios and then the changes after implementation of the No-Winter fertiliser timings.

5.1.1. Baseline scenarios

The 16 scenarios were too many to effectively show all results so in the figures below the time series from the “Light-Dry” (i.e., the soil with the lower plant available water (PAW) and lower rainfall) are shown as a time series and then all of the scenarios within the region as box plots.

Figure 6 shows the annual amount of pasture gazed plus that harvested for silage (see also Table 7). Across soils and climates, average annual harvested (grazed or cut for silage) pasture production ranged from 13.2 (Northland) to 15.8 t DM /ha /yr (Canterbury). There was a net sale of silage from the Northland scenarios (Figure 7; net purchase is silage fed minus silage made) indicating that the simulated farm could have supported a higher stocking rate. The scenarios in all other regions required net purchase of feed, ranging from 5% of that grazed in the Waikato to 48% in Canterbury.

Nitrogen leaching (Figure 8, Table 7) ranged from 12 (Northland) to 211 (Canterbury) kg N /ha /yr once averaged across years. These values reflect the combination of the vulnerability to leaching (primarily driven by soil and climate) and the selected stocking rates. These values are higher than the scenarios presented in Bryant et al. (2019) but are consistent given the differing stocking rates, soils, climates and fertiliser rates. Note that the high stocking rates in the South Island simulations, particularly in Canterbury, are associated with quite high leaching rates. The simulations showed substantial year-to-year variability. Some of that variability will have been enhanced by the decision to output values only on grazing dates. With this setting, all the leaching after the date of the previous grazing becomes ‘assigned’ to the next grazing event, even if this crosses a year boundary. For example, if the paddock was grazed on 1 December 2020 and then next on 1 January 2021, all the leaching from December 2020 would be assigned to 2021.

Table 7: Summary of scenario outputs by Region for the Baseline fertiliser scenario and Climate-Soil combination showing annual averages with inter-annual standard deviations in parentheses for Pasture Grazed (t DM /ha /yr), Silage Fed (t DM /ha /yr), Number of Silage Feeding Events (events /yr), Net Amount of Silage Imported (t DM /ha /yr), and Nitrogen Leached (kg N /ha /yr). Details of the farm systems by regions, soils and climates are given in Section 3.

Climate-Soil	Grazing Events	Pasture Grazed	Silage Fed	Net Silage Imp.	Feeding Events	Nitrogen Leached
Northland						
Drier-Lighter	11.5 (1.5)	10 (1.3)	0.5 (0.4)	-1.9 (1)	1.4 (0.8)	25.7 (11.8)
Drier-Deeper	12.6 (1.7)	10.8 (1.3)	0.6 (0.5)	-2.1 (1)	1.4 (0.7)	12.7 (6.7)
Wetter-Lighter	12 (1.6)	10.3 (1.3)	0.5 (0.4)	-2.1 (0.9)	1.3 (0.7)	31.3 (12.8)
Wetter-Deeper	13.1 (1.7)	11.1 (1.3)	0.4 (0.4)	-2.5 (0.9)	1.2 (0.8)	16.1 (7.4)
Waikato						
Drier-Lighter	11.9 (1.5)	12.9 (1.4)	1.5 (0.5)	0.6 (0.7)	6.5 (1.3)	54.3 (18)
Drier-Deeper	13 (1.6)	13.9 (1.6)	1.3 (0.6)	0.4 (0.9)	6 (1.7)	39.8 (16.3)
Wetter-Lighter	13.4 (1.5)	13.5 (1.4)	1.7 (0.7)	1 (0.9)	6.5 (1.3)	87.7 (18.3)
Wetter-Deeper	14.2 (1.2)	14.1 (1.1)	1.7 (0.7)	0.9 (0.9)	6.6 (1.4)	73.4 (16.4)
Canterbury						
Drier-Lighter	15 (0.8)	16.5 (1.1)	7 (0.8)	6.9 (0.8)	14.3 (1)	192 (74)
Drier-Deeper	15 (0.8)	16.6 (1.1)	7.1 (0.8)	7 (0.8)	14.3 (1.2)	158.1 (84.3)
Wetter-Lighter	14.4 (0.9)	15.1 (1.3)	7.4 (0.6)	7.4 (0.7)	13.8 (1.1)	210.9 (32.5)
Wetter-Deeper	14.3 (1)	14.9 (1.3)	7.4 (0.6)	7.4 (0.6)	13.5 (1.2)	179.7 (47.1)
Southland						
Drier-Lighter	14.8 (0.7)	16 (1)	3.1 (0.4)	2.9 (0.4)	7.7 (0.9)	94.4 (38.3)
Drier-Deeper	14.9 (0.7)	16.1 (1)	3.1 (0.5)	2.7 (0.5)	7.4 (1.2)	53.3 (20.4)
Wetter-Lighter	13.7 (0.7)	14 (0.9)	3.9 (0.4)	3.8 (0.4)	9.6 (1.4)	137.6 (30.6)
Wetter-Deeper	13.7 (0.7)	13.7 (1)	4.2 (0.4)	4 (0.4)	9.4 (1.3)	105.3 (22.9)

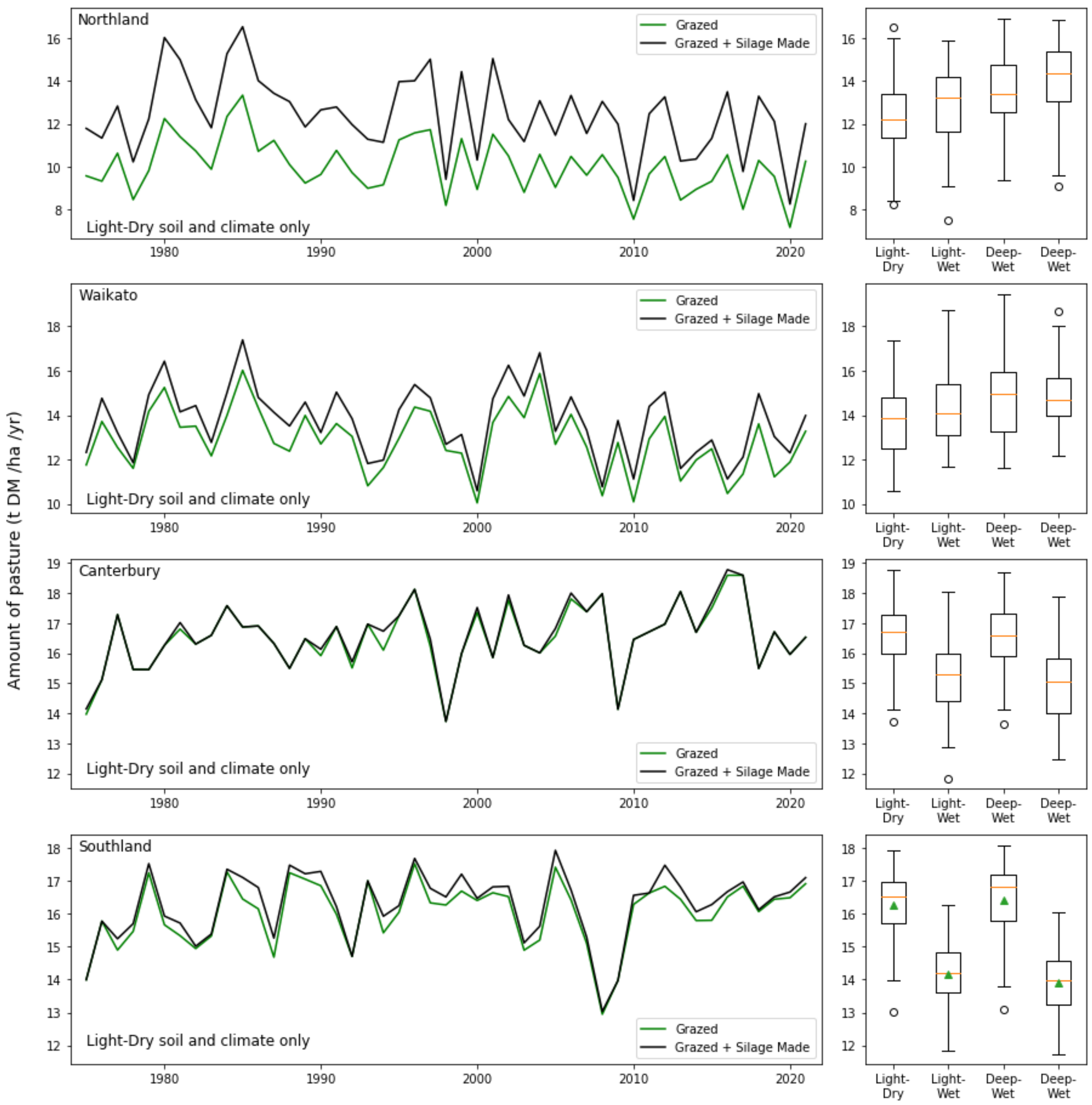

Figure 6: Time series plots (left) of the amount of pasture grazed in situ (green) plus that harvested for silage (black) by region with data shown only for the light soil and drier climate. Box plots (right) of the pasture grazed or harvested for silage by region for all soil and climate combinations.

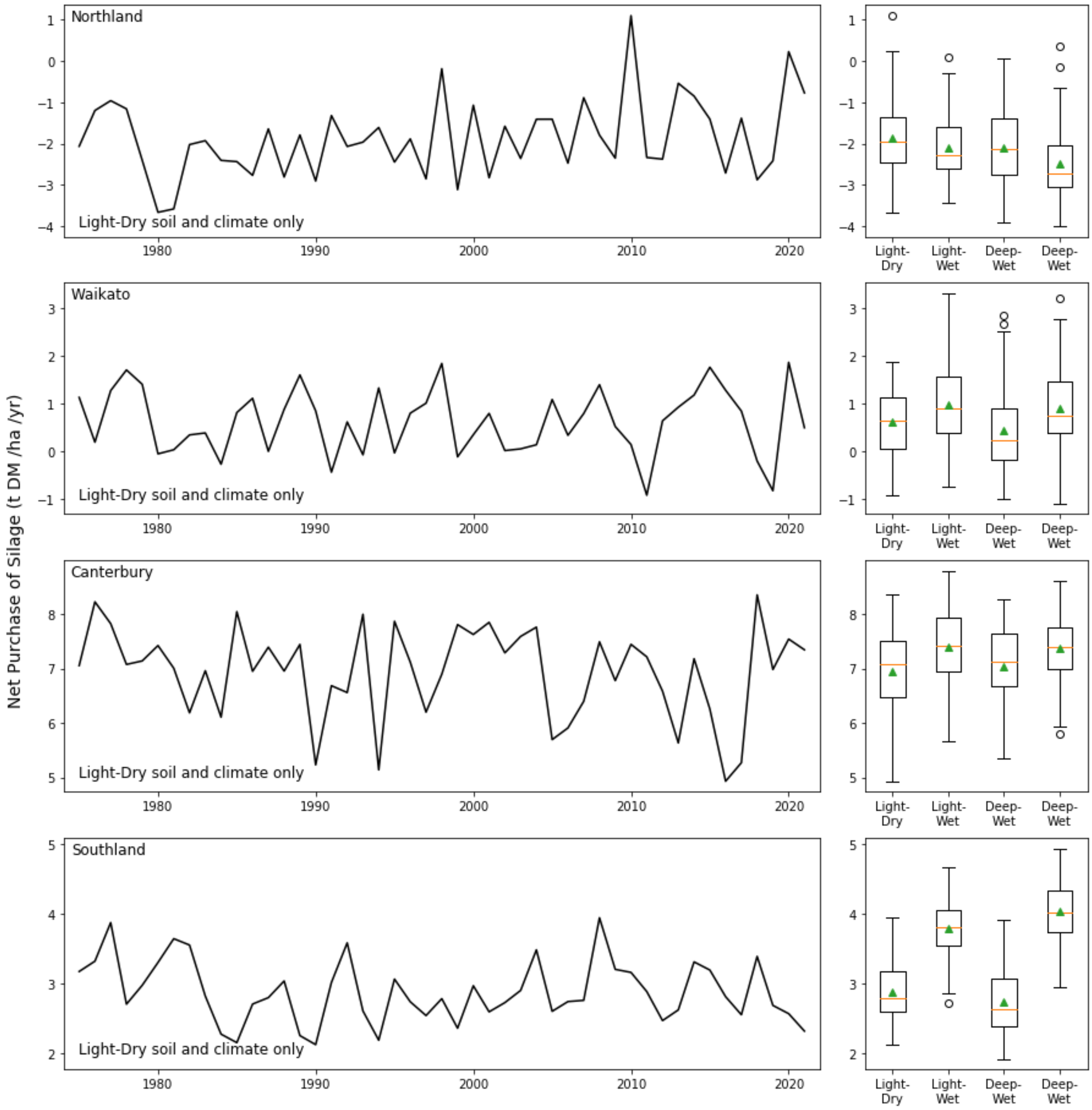

Figure 7: Time series plots (left) of the net amount of silage imported (e.g., purchased, a negative value is a net sale) by region with data shown only for the light soil and drier climate. Box plots (right) of the net silage imported by region for all soil and climate combinations.

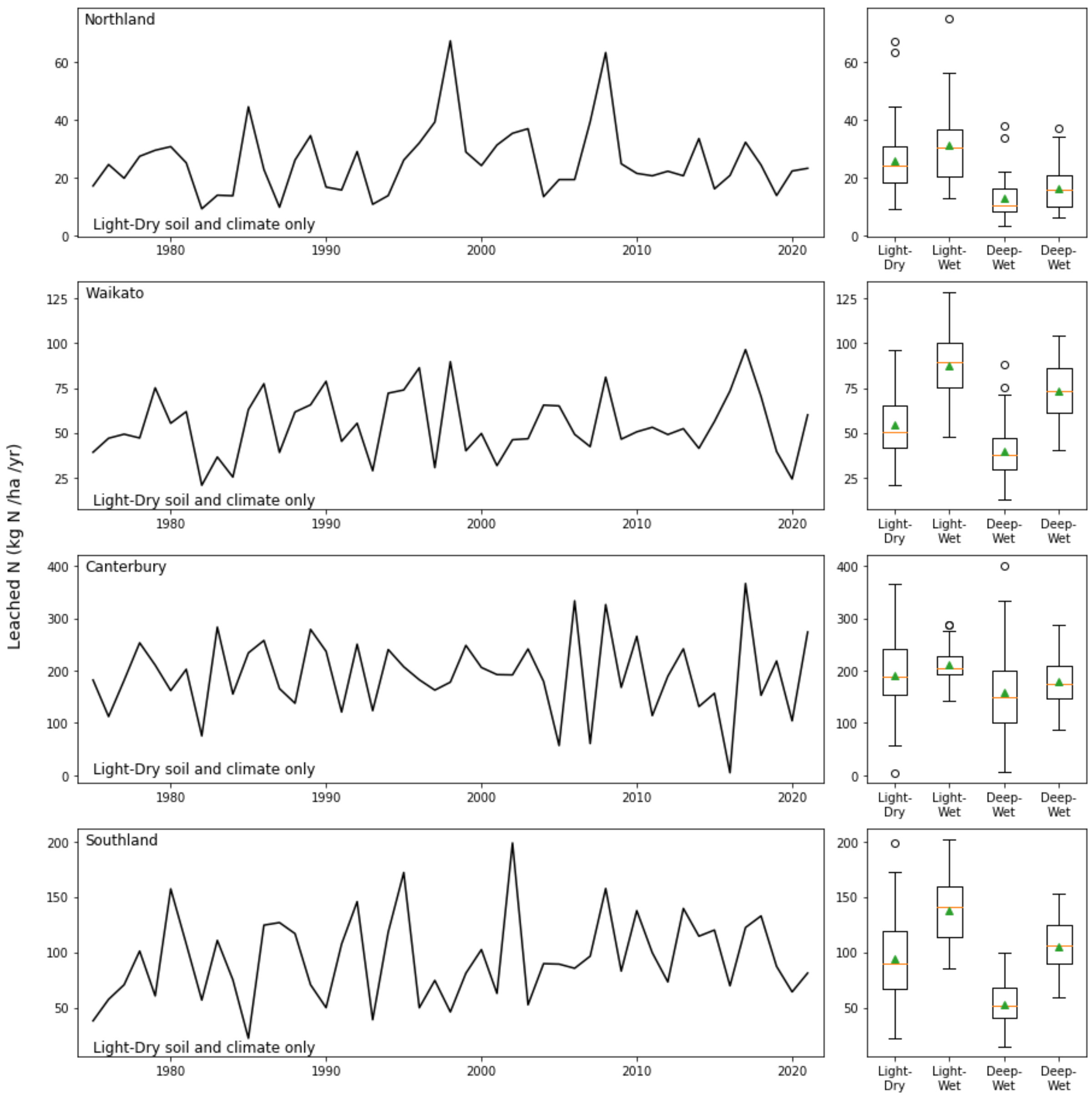

Figure 8: Time series plots (left) of the simulated amount leaching of N by region with data shown only for the light soil and drier climate. Box plots (right) of leaching by region for all soil and climate combinations.

5.1.2. Nitrogen response rates

Before examining the effect of the No-Winter scenario, it is useful to consider the nitrogen response rates (NRR). NRR in the months affected by the fertiliser scenarios. Figure 9 and Table 8 show the NRR (for the light-dry soil-fertiliser combinations only, see Figures A1-A4 for other soils and climates) for the four regions. NRR values from months in which fertiliser was applied in the Baseline scenarios but not the No-Winter are shown in blue. Values in green are the new applications months in the No-Winter scenarios.

With the exception of the March N application that was moved to April in the Waikato, Table 7 and Figure 9 show that the No-Winter fertiliser scenario results in increased NRR that are often also more reliable (i.e., with a lower standard deviation). Given this, it seems likely that the greatest effect of the No-Winter scenario might be to reduce reliance on silage (or increase the amount of silage sold). However, the changed fertiliser dates will also change the pattern of pasture growth within the year and if this gives the No-Winter scenarios a poorer match to energy demand there may be a need for a greater number of silage feeding events.

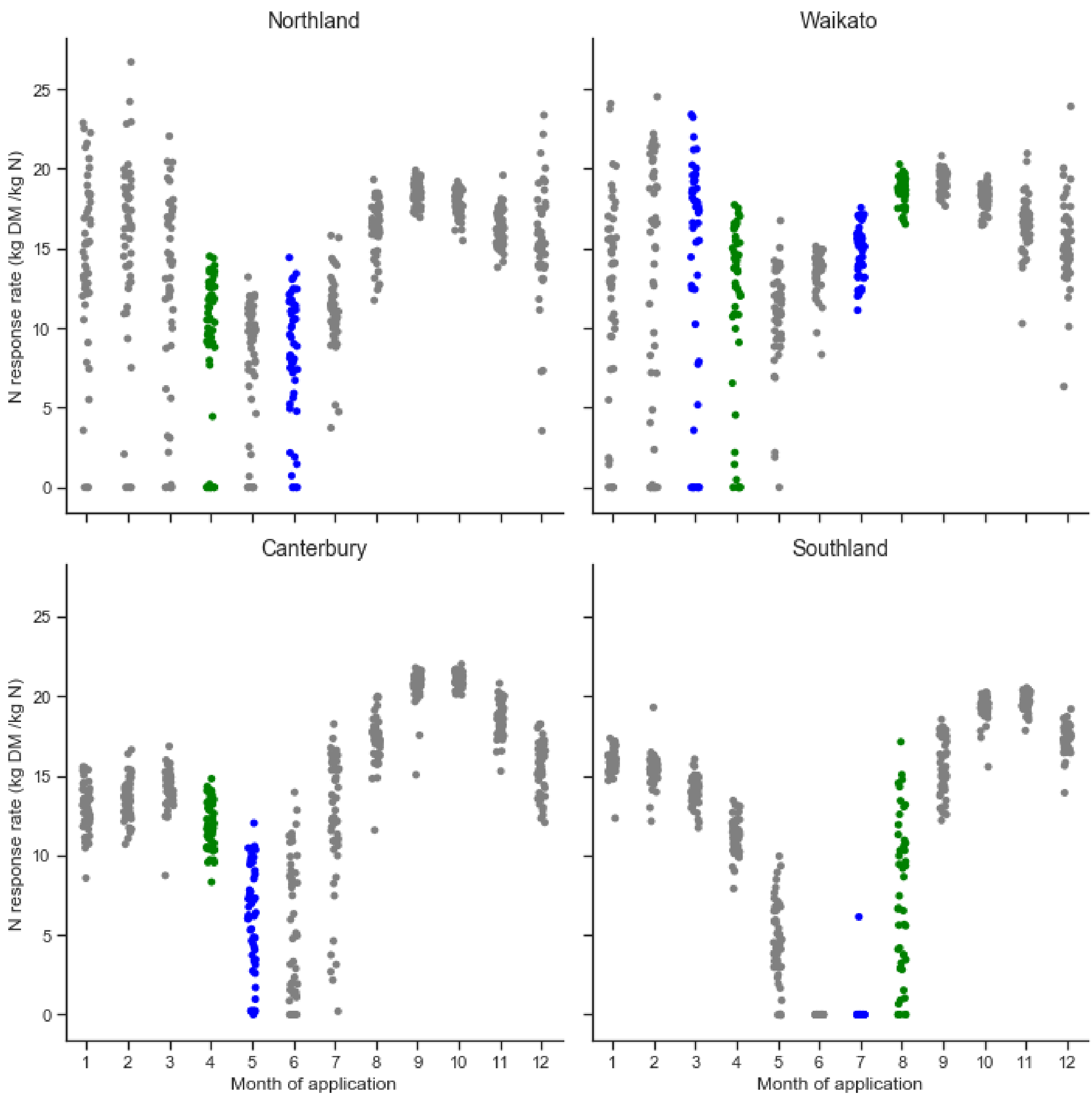

Figure 9: Strip plots of the two-month nitrogen response rate (kg DM /kg N) by region and month of application for the light soil and drier climate only (other soil-climate combinations can be seen in the Appendix). The variation within month is by year of application (1972 to 2021). Blue symbols show application months removed from the Baseline scenarios while the green symbols show the new months of application under the "No Winter" scenarios. See the Methods section and Appendices for more detail.

Table 8: Nitrogen response rates for the Light-Dry scenarios for the four regions showing data only for the application months affected by the fertiliser scenarios. The data shows the mean across years and standard deviation. See Figures 4 and A1-A4 for additional response rates.

Region	Baseline	No-Winter
Northland	8.2 (4.1)	9.1 (4.8)
Waikato	14.6 (1.6)	18.7 (0.9)
	13.9 (7.4)	11.2 (5.8)
Canterbury	6 (3.3)	11.9 (1.5)
Southland	0.1 (0.9)	7.3 (4.9)

5.1.3. Farm System Effects

Figures 10 and 11 and Table 7 summarise the primary simulation model outputs by region for all the Baseline scenarios with the differences found in the No-Winter scenarios in Table 9. None of the differences in Table 9 have statistical or practical significance. It was considered if the change in fertiliser timing in the No-Winter scenario might result in a greater need for feeding events but any such effects are very minor.

This lack of effect is largely because the total amount of N fertiliser applied was not changed under the scenarios. The change in timing generally resulted in an increased NRR. Because the farm system 'rules' were to maintain milk solids production to a pre-defined target, and any additional pasture grown was offset by changes in silage made, fed, or imported.

It is likely that the purpose of disallowing the application of N fertiliser in winter was to reduce leaching. In these simulations, there was essentially no difference caused by the changes in fertiliser timing. Had the farm system rules been set up differently, for example allowing higher stocking rates in response to more pasture being grown then it is likely that simulated leaching would have increased.

It should be noted that these simulations assume no loss of N by overland flow / runoff. Runoff events are more likely in winter so moving fertiliser applications away from winter may reduce N losses by this mechanism.

Table 9: Difference between the No-Winter and Baseline scenario outputs by Region and Climate-Soil combination (D-L, Drier-Lighter; D-D, Drier-Deeper; W-L, Wetter-Lighter; W-D, Wetter-Deeper) showing annual averages with inter-annual standard deviations in parentheses for Pasture Grazed (t DM /ha /yr), Silage Fed (t DM /ha /yr), Number of Silage Feeding Events (events /yr), Net Amount of Silage Imported (t DM /ha /yr), and Nitrogen Leached (kg N /ha /yr). Details of the farm systems by region, soils and climates are given in the Appendices.

Climate-Soil	Grazing Events	Pasture Grazed	Silage Fed	Net Silage Imp.	Feeding Events	Nitrogen Leached
			Northland			
D-L	-0.02	0.01	-0.07	-0.06	-0.09	0.34
D-D	-0.06	0.05	-0.05	-0.01	-0.11	0.3
W-L	0	0.11	-0.03	0.08	0.09	1.21
W-D	0.06	0.18	0.02	0.13	0.04	0.74
			Waikato			
D-L	0.06	0.08	-0.06	0.04	-0.15	0.33
D-D	0.04	0.11	0.04	0.1	-0.02	0.81
W-L	-0.06	0.02	-0.08	-0.02	0.13	0.62
W-D	-0.04	-0.01	-0.03	0	-0.26	1.84
			Canterbury			
D-L	0	-0.02	0.06	0.07	0.04	2.32
D-D	0	-0.03	0.04	0.03	0.02	1
W-L	0	0.01	0.04	0.06	0.04	1.73
W-D	0	-0.03	0.03	0.03	0.04	1.12
			Southland			
D-L	0.02	0.01	0	-0.01	0	-0.42
D-D	0	0.01	-0.01	-0.02	0	-0.24
W-L	0.04	0.04	0	-0.02	0	-1.17
W-D	0.02	0.03	-0.01	-0.03	-0.06	-0.69

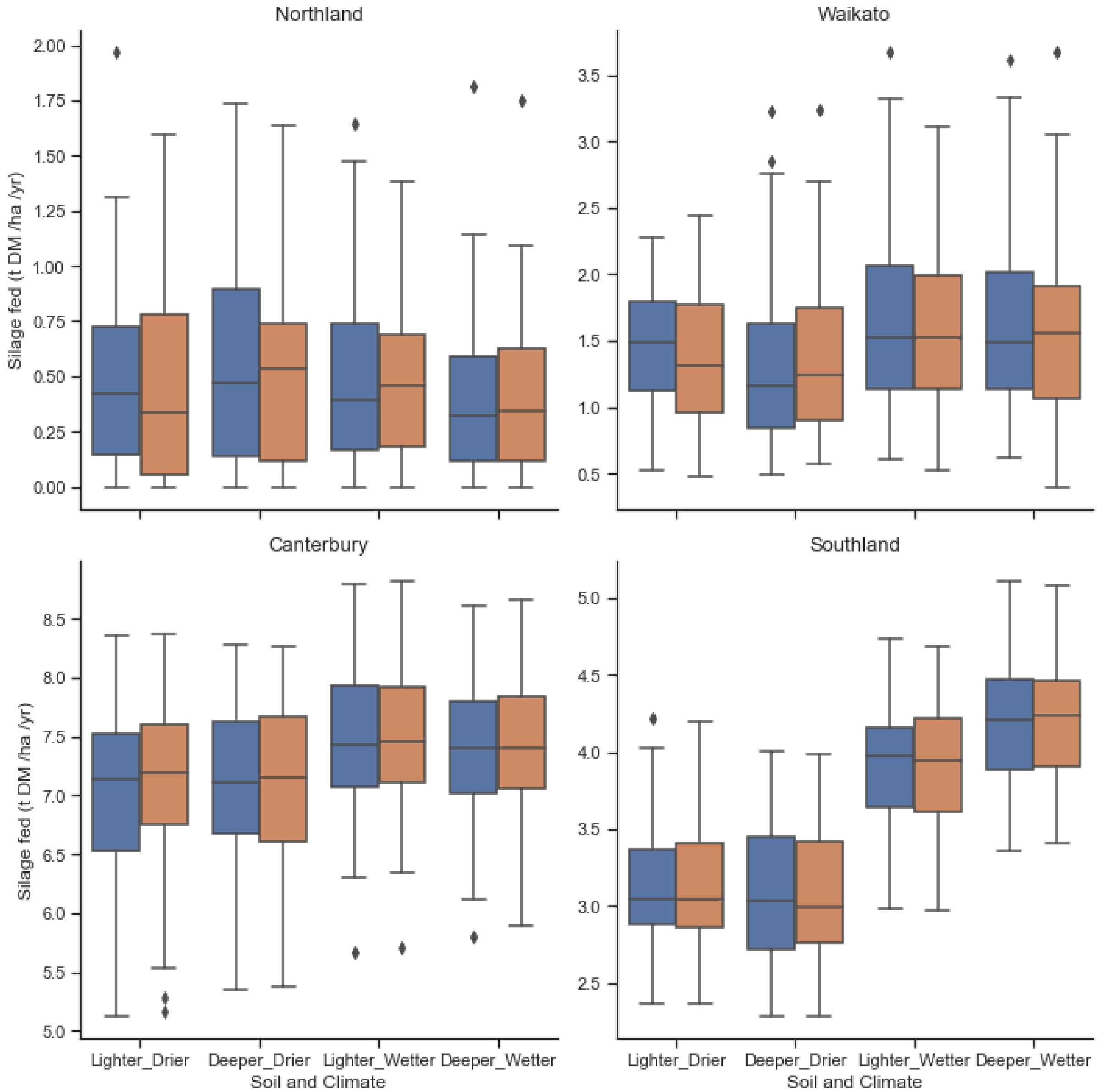

Figure 10: Box plots showing the quantity of silage fed (t DM /ha /yr) by region (as labelled) with the Baseline scenarios in blue and the No-Winter scenarios in orange.

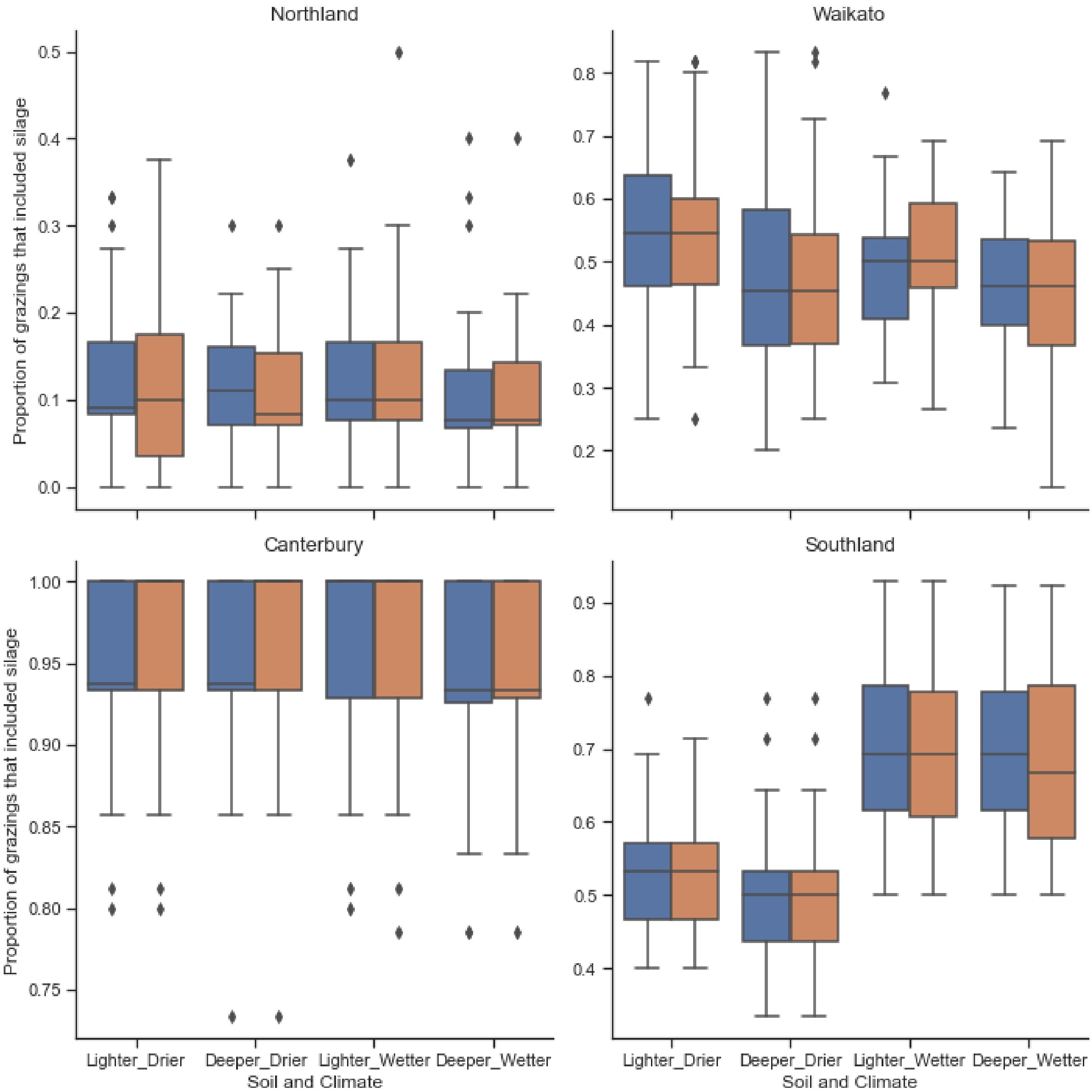

Figure 11: Box plots showing the proportion of grazing events at which silage was fed by region (as labelled) with the Baseline scenarios in blue and the No-Winter scenarios in orange.

6. Conclusions

This short review report provides an assessment of published and expert evidence on the impact of winter/early spring nitrogen (N) fertiliser application under different conditions grazed pasture systems across different areas of New Zealand. The review is further supplemented by scenario modelling using The Agricultural Production Systems sIMulator (APSIM).

Available evidence suggests that a feed shortage in early spring is probably best met by supplementary feeding or by N applications sufficiently late winter that the nitrogen response rate has risen from the winter lows. By "late winter", we mean once soil temperatures have increased sufficiently to increase potential pasture growth and the balance between evaporation and rainfall is such that the risk of loss by leaching has substantially reduced. The calendar timing will vary from region to region but also by year within region. Tools to assist farmers in this decision may be useful. Also temporary immobilisation by the soil microbial biomass in late winter will further reduce losses of applied N and can provide a relatively large residual pasture response.

Direct leaching of N from fertiliser in grazed pasture systems is generally low (< 10% of N fertiliser applied) if application rates are not excessive (i.e., < 200 kg N ha^{-1} yr^{-1}) and are synchronised with periods when pasture require N and they are actively growing. There has been some limited research in New Zealand investigating the effect of timing (season) of N fertiliser application on N volatilisation from pasture, and with mixed results. Winter nitrous oxide (N_2O) emission factor (EF) (N_2O-N emitted as a % of N applied) is reported to be highest of all seasons.

Any impact of a change in N fertiliser policy on animal welfare would be *via* feed shortages on farm. A change in farm management, e.g., making and feeding more supplements or forage crops, may be needed to address those regular feed shortages that are expected and so can be planned for in advance.

The APSIM results suggest that moving fertiliser applications away from winter towards the prior autumn or following spring also meant that the applications were at a time of year when nitrogen response rate was higher than in the Baseline winter applications. The No-Winter scenario resulted in minimally changed simulation outputs – none were statistically or practically significant. Simulated leaching was similarly unaffected.

The scenario rules prevented the farm intensification (increased milk production and/or increased cow numbers) that might otherwise result from moving N applications from winter to a time of year when NRR is higher. If such intensification occurs then leaching may increase.

It should be noted that these simulations do not include overland flow processes. Therefore, this study cannot determine if moving fertiliser applications away from winter, when runoff events are more likely, would reduce N losses by surface flow mechanisms.

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Appendices

A APSIM Modelling

The simulation model, Agricultural Production Systems Simulator (www.apsim.info) (APSIM; Holzworth et al., 2014) r4191, was used for the work described here. The principal models used included: AgPasture (Li et al., 2011); SoilTemperature2 (based on Campbell, 1985); Micromet (Snow and Huth, 2004); SWIM3 (Huth et al., 2012); and SoilNitrogen (SoilN as described by Probert et al., 1998, ported to the .NET environment) which includes denitrifrication processes. The simulations also used the gridded-patch methodology described and evaluated by Snow et al., (2017) to represent the effect of urine patches on pasture growth and leaching. Losses of N to volatilisation were not simulated.

Farm system simulations

Farm system simulations were performed for fertiliser policies without and with a ban on winter applications in consultation with FANZ. The simulations were of a single paddock within the grazing rotation context of a whole farm and included a simple dairy cow model based on the lactation curve equations in Wood (1967) combined with ME requirements sourced from Dairy NZ (2017). A fourth parameter was added to the Wood equation to scale milk production to the required annual milk production. Assumptions about the number, loading and size of urine patches was based on a combination of Shorten et al. (2021) and previous work (P. Shorten and B. Welten, AgResearch, unpublished data). The basic assumptions of the farm systems were:

- a set and constant stocking rate with no replacement stock on-farm;
- a prescribed milk solids production, and therefore also metabolisable energy (ME) intake, target where if there was not sufficient pasture available then the cows were supplemented with silage; and
- if there was more pasture than needed by the cows then it was harvested as silage regardless of the time of year.

These assumptions reflect an unattainable 'ideal' of rule-based management but allows for comparison of scenarios. Note also that off-paddock (e.g., lanes, milking sheds, effluent) effects were not included.

Irrigation was applied in the Canterbury and Southland scenarios. The settings were equivalent to a well-designed and maintained centre-pivot irrigator with irrigation used to top up the soil water to field capacity as needed but with a return period no less than two days for shallow soils and 4 days for deep soils.

Because changing the timing of fertiliser applications will likely change pasture production, the effect of changing N fertiliser policy on production will primarily be reflected in the amount of silage made/fed/imported and perhaps the number of silage feeding events.

Sixteen scenarios were simulated. In each of four regions (Northland, Waikato, Canterbury, Southland), two climates and two soils were selected for simulation. Farm systems and fertiliser settings are given in Table A1, climate information in Table A2, and soil data in Table A3. With the addition of the Baseline fertiliser (i.e., permitting fertiliser applications in winter) and a No-Winter policy this resulted in 32 simulations that were run from 1972 to 2021. The first three years of simulation outputs were discarded as this time allows the full heterogeneity in soil N resulting from urine patch deposition to develop.

The key outputs from the simulations used in this report were:

- pasture grazed;
- number and timing of grazing events;
- silage fed;
- number of silage feeding events;
- silage made; and
- nitrogen leached.

These values were output from the simulation at each grazing event and, where necessary, accumulated the outputs from the previous grazing event. After discarding the initial three years of outputs the data was summarised into annual values. A calendar year was used for simplicity of analysis.

Table A1: Key farm systems and fertiliser applications for the farm systems in the regions simulated.

	Northland	Waikato	Canterbury	Southland
Stocking rate (cows /ha)				
	2.3	2.9	3.6	3.0
Target milk solids production (kg MS /cow /season)				
	340	390	465	440
Cows wintered off?				
	No	No	Yes	Yes
Date calving starts				
	12-Jul	15-Jul	01-Aug	08-Aug
Date cows dried off				
	15-Apr	21-Apr	08-May	15-May
Was the paddock irrigated?				
	No	No	Yes	Yes
Annual N fertiliser applied (kg N /ha /year)				
	99	132	189	170
Baseline (first row) and No-Winter (second row) fertiliser dates[1]				
	JFMAM**J**J**A**S**O**ND	JF**M**AMJ**J**A**SO**ND	JF**M**A**M**JJ**ASOND**	JF**M**AMJ**J**A**SO**N**D**
	JFM**A**MJJ**A**S**O**ND	JFM**A**MJJ**ASO**ND	JF**MA**MJJ**ASOND**	JF**M**AMJJ**ASO**N**D**

Table A2: Characteristics of the climates used in the scenarios.

Region and climate type	Approximate location	Latitude	Longitude	Average rainfall (mm/year)	Meant air temperature (C)
Northland – drier	Tangiteroria	-35.825	174.025	1548	15.4
Northland – wetter	Waiotu	-35.525	174.225	1834	15.3
Waikato – drier	Ruakura	-37.775	175.325	1143	13.8
Waikato – wetter	Matuwai	-38.375	177.525	1814	11.2
Canterbury – drier	Darfield	-43.475	172.075	851	11.4
Canterbury – wetter	Alford forest	-43.575	171.525	1252	10.0
Southland – drier	Balclutha	-46.225	169.725	736	10.1
Southland – wetter	NW Mokoreta	-46.375	169.175	1371	9.6

Table A3: Characteristics of the soils used in the scenarios.

Region and soil type	Soil Identifier	Plant-available water to 0.6 m
Northland – lighter	Clay (Kerikeri No1353)	92
Northland – deeper	Silt loam (Kaikohe No1344)	127
Waikato – lighter	Loam (Hamilton No1354)	90
Waikato – deeper	Loam (Hamilton, Horotiu No1356)	130
Canterbury – lighter	Silt loam (Lincoln No1417)	90
Canterbury – deeper	Silt loam (Darfield No1385)	121
Southland – lighter	Loam (Balclutha No1394)	85
Southland – deeper	Silt loam (Woodlands No1328)	133

Nitrogen response rate simulations

Nitrogen response rate simulations were performed to better explain some of the farm system outputs. The same soil, climates and irrigation settings as above were used (see Tables A1-A3), and an N input rate of 30 kg N /ha was assumed (the N applications in the farm system simulations varied between 27 and 34 kg N /ha). Simulations were run to mimic physical fertiliser response trials. The N response rate (NRR, kg DM /kg N) was calculated as the amount of pasture accumulated in the two months after fertiliser application minus the pasture accumulated in a no-fertiliser paired simulation all divided by the 30 kg N /ha fertiliser application. Pairs of simulations were run for the 15th of each month from 1972 to 2021 in each of the 16 soil-climate combinations. There are no issues with heterogeneity in this system, so all data were retained.

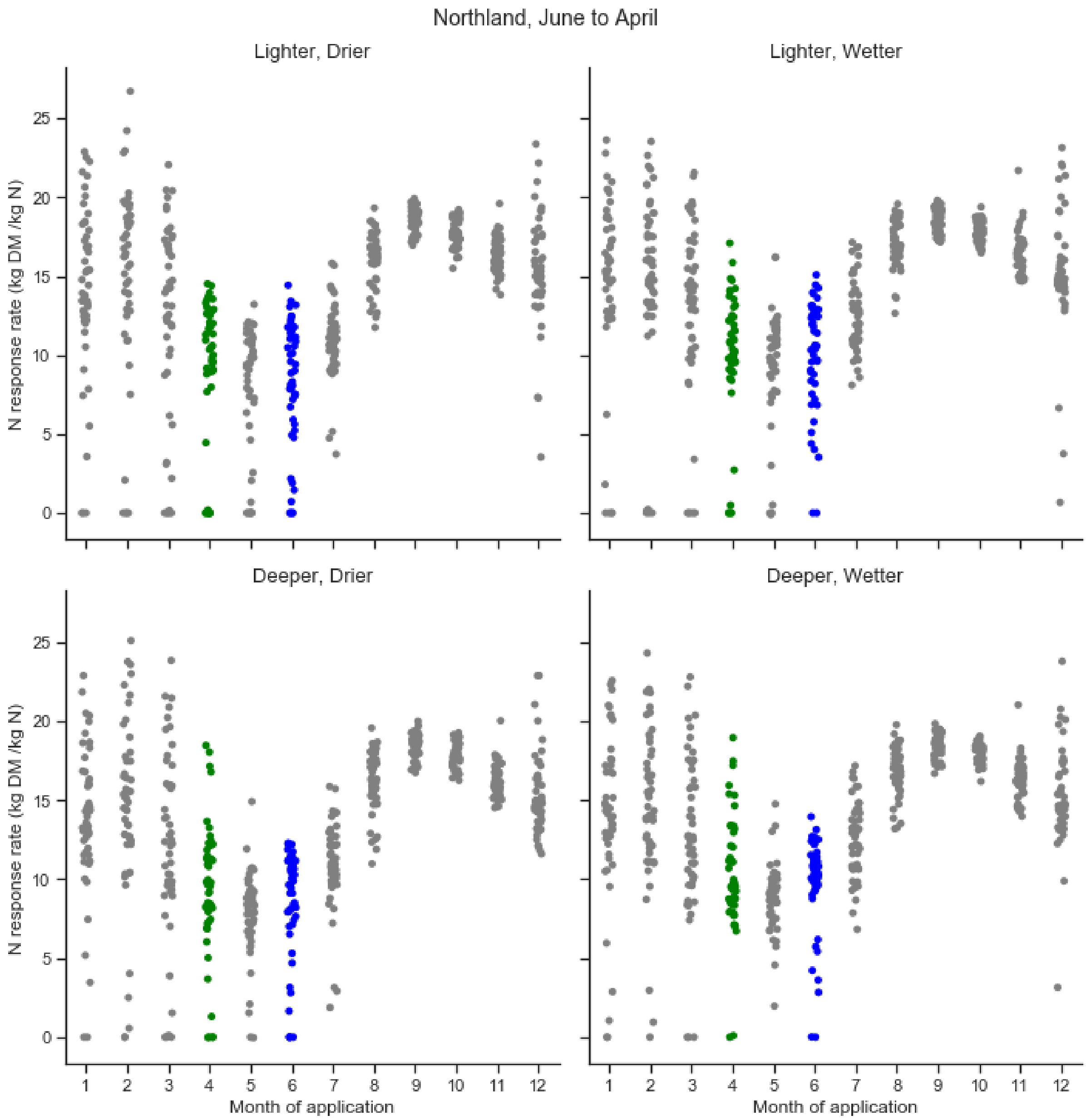

Figure A1: Strip plots of the two-month nitrogen response rate (kg DM /kg N) for Northland by month of application for the soil and climate as labelled. The variation within month is by year of application (1972 to 2021). Blue symbols show application months removed from the Baseline scenarios while the green symbols show the new months of application under the "No Winter" scenarios. See the Methods section for more detail.

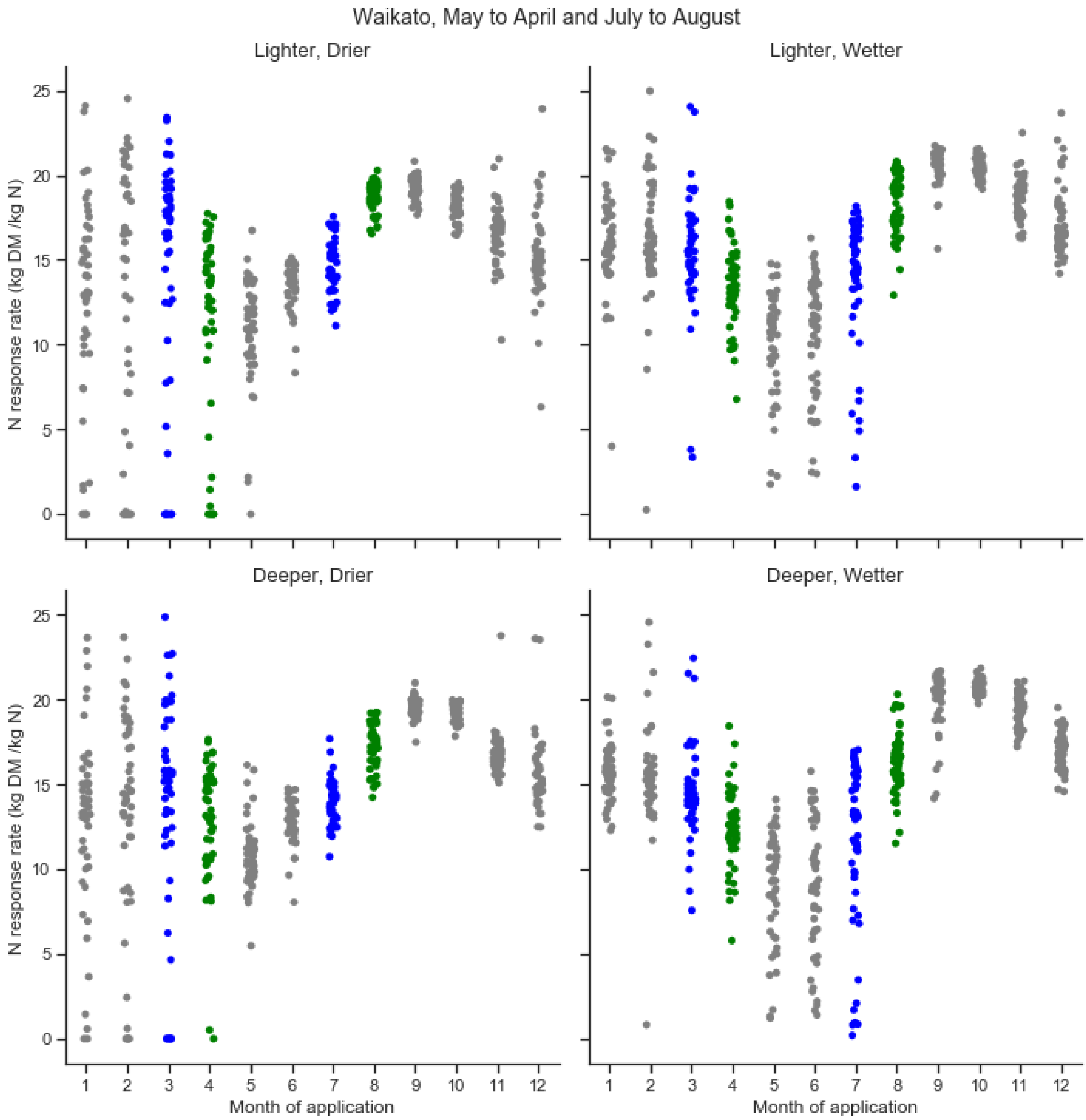

Figure A2: Strip plots of the two-month nitrogen response rate (kg DM /kg N) for Waikato by month of application for the soil and climate as labelled. The variation within month is by year of application (1972 to 2021). Blue symbols show application months removed from the Baseline scenarios while the green symbols show the new months of application under the "No Winter" scenarios. See the Methods section for more detail.

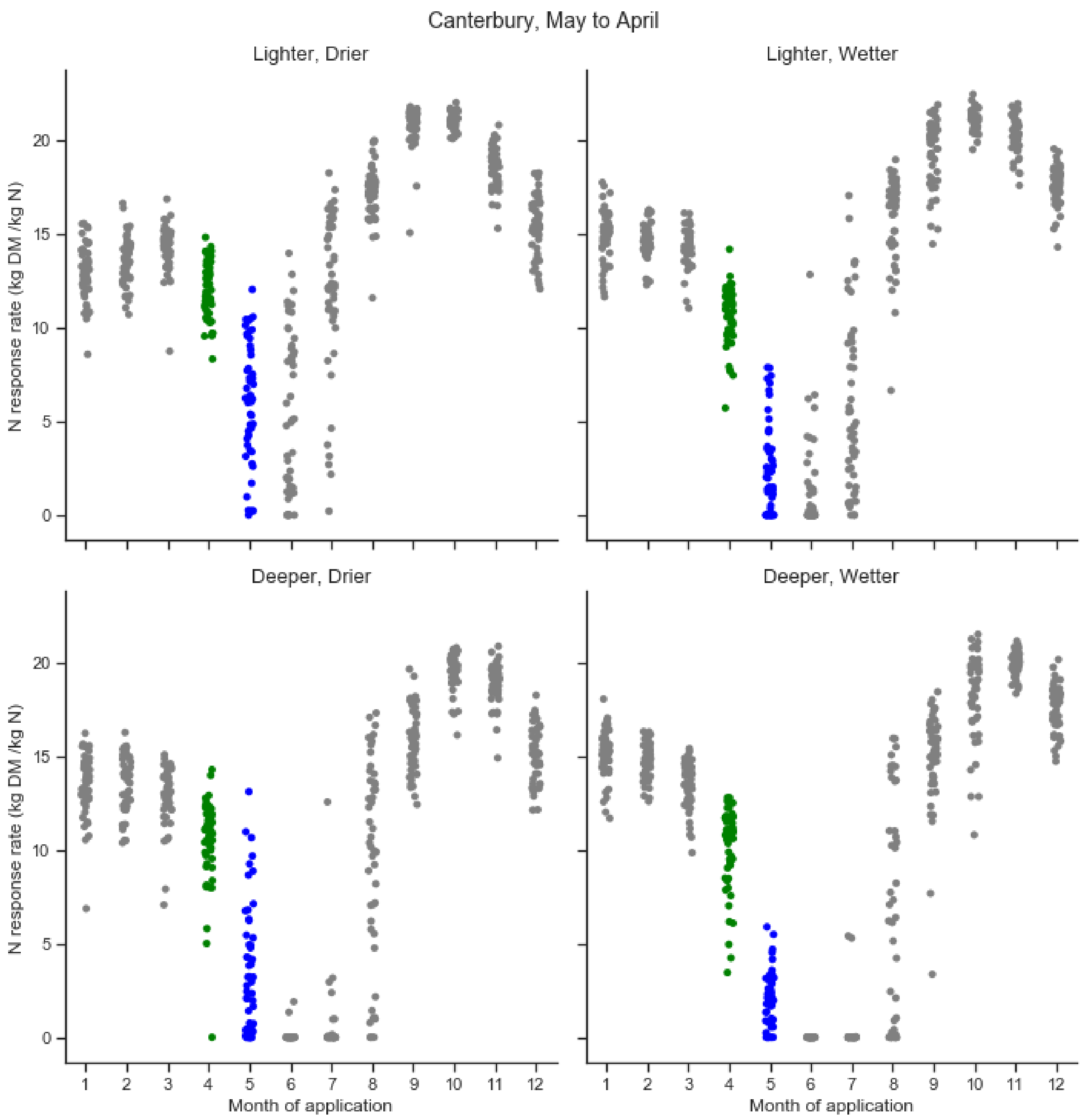

Figure A3: Strip plots of the two-month nitrogen response rate (kg DM /kg N) for Canterbury by month of application for the soil and climate as labelled. The variation within month is by year of application (1972 to 2021). Blue symbols show application months removed from the Baseline scenarios while the green symbols show the new months of application under the "No Winter" scenarios. See the Methods section for more detail.

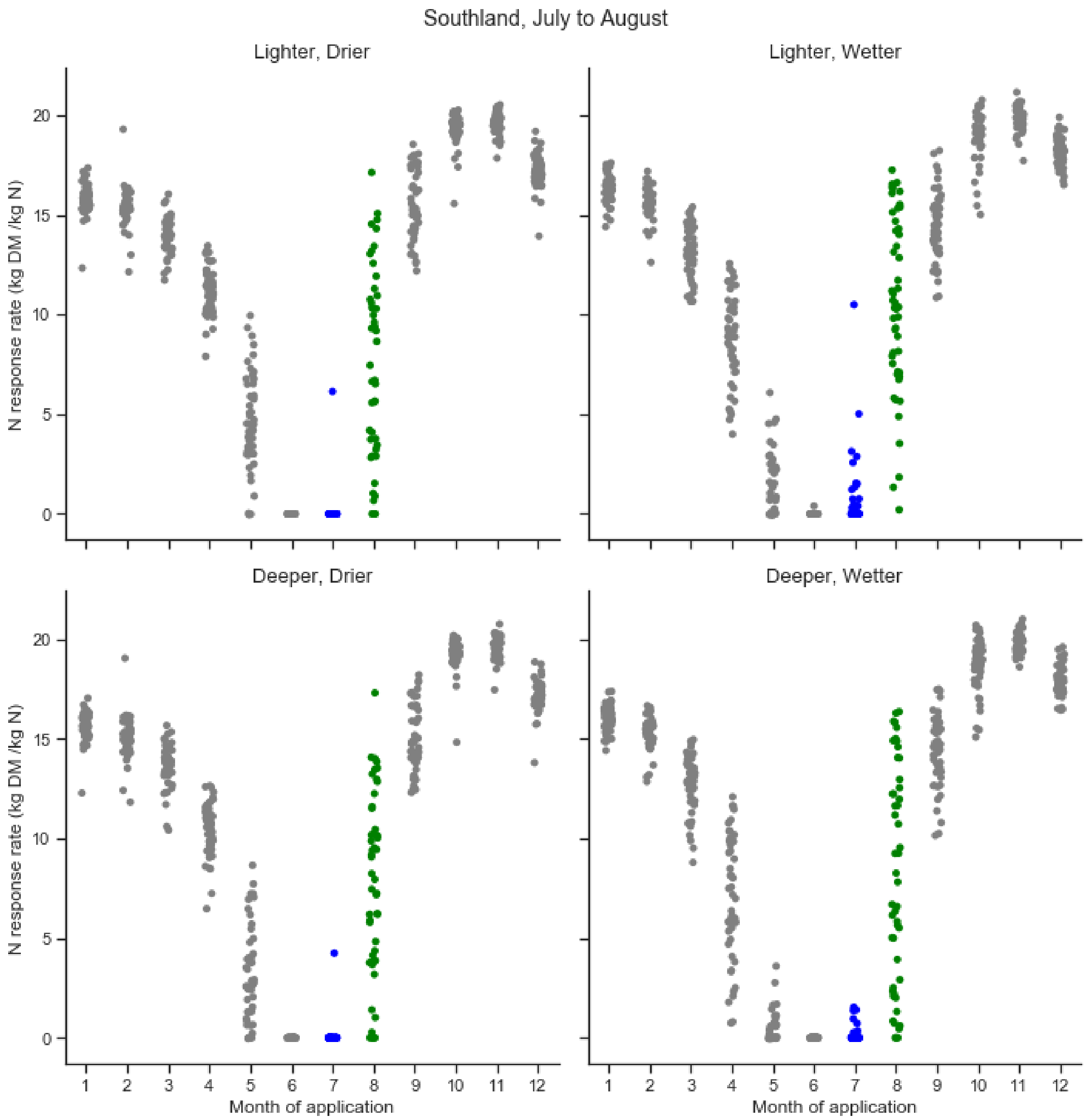

Figure A4: Strip plots of the two-month nitrogen response rate (kg DM /kg N) for Southland by month of application for the soil and climate as labelled. The variation within month is by year of application (1972 to 2021). Blue symbols show application months removed from the Baseline scenarios while the green symbols show the new months of application under the "No Winter" scenarios. See the Methods section for more detail.