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CAN A WINTER-SOWN CATCH CROP REDUCE NITRATE LEACHING LOSSES AFTER WINTER FORAGE GRAZING?

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Abstract
Direct grazing of winter forage crops to feed non-lactating, pregnant dairy cows prior to calving is a common management practice in the New Zealand South Island. However, the high crop yields per hectare grazed, combined with a high stocking density of cows, means this potentially leads to large amounts of urinary nitrogen (N) deposited on bare, wet soil, that in turn, could lead to high nitrate leaching losses. We undertook a study to simulate a winter forage grazing (WFG) event using field lysimeters planted with a kale (*Brassica oleracea* L.) crop. We report the effect of delaying sowing a "catch crop" of oats (*Avena sativa* L.) following simulated WFG on nitrate leaching losses from urine applied at different times throughout the winter.

A catch crop sown between 1 and 63 days after urine deposition in early winter reduced N leaching losses from urine patches by ~34% on average (range 19-49%) over the winter-spring period compared with no catch crop. Generally, the sooner the catch crop was sown following crop harvest, the greater the uptake of N by the catch crop and the greater the reduction in nitrate leaching losses.

The results indicate that sowing of a catch crop following winter crop grazing could be an effective management strategy to reduce nitrate leaching as well as increase the N use efficiency of dairy winter forage grazing systems.

Keywords
Kale, nitrate leaching, oats, catch crop, lysimeter, cereal, wintering systems

Introduction

In the New Zealand dairy industry, and particularly in the South Island, pregnant, non-lactating dairy cows commonly graze winter forage crops to achieve body condition score targets for the start of calving in early spring (Judson *et al.*, 2010). Forage crops such as kale (*Brassica oleracea* L.) are normally sown in the previous spring, reaching yields of 10–16 t DM/ha when grazing starts in winter (Brown *et al.*, 2007). Crops are grazed for 8-10 weeks, after which the cropped area remains fallow until the next crop is sown in late spring (2-3 months later). While these systems are an effective way to provide the large quantities of feed needed at a time of the year when the growth of pasture, the most common feed for dairy cows, is limited by cold temperatures, they can lead to large nitrate leaching losses. There is a high potential for nitrate leaching under intensive pastoral grazing systems and losses can increase disproportionately with increasing stocking rate and fertiliser N use (Ledgard *et al.*, 1999; Monaghan *et al.*, 2007; Cameron *et al.*, 2013). Increased nitrate levels in drinking water are undesirable and can also lead to excessive aquatic plant growth and eutrophication within a water catchment area (Ministry for the Environment, 2010).

Mitigation options to reduce N loss from intensively-grazed pastures in New Zealand have been reviewed by Ledgard *et al.* (1999), Monaghan *et al.* (2007) and Cameron *et al.* (2013). However, winter forage crop grazing (WFG) presents a new challenge for reducing N losses because large volumes of urine are deposited onto bare soil with no opportunity for plant uptake of N at a time of year when drainage rates are typically high. Whilst a fast-growing catch crop has been reported as a useful mitigation strategy for reducing nitrate leaching loss in cereal cropping systems (McLenaghen *et al.*, 1996; Francis *et al.*, 1998; Shepherd, 1999; Di & Cameron, 2002), there is no information on the effect of using a catch crop to reduce nitrate leaching from WFG systems. With a number of recent New Zealand WFG studies reporting nitrate leaching losses ranging from 52-173 kg N/ha (Shepherd *et al.*, 2012; Smith *et al.*, 2012; Monaghan *et al.*, 2013; Malcolm *et al.*, 2015) there is recognition that these need to be reduced if these open grazing systems are to remain.

We report a field-based lysimeter experiment designed to quantify the effectiveness of sowing oats (*Avena sativa* L.) as a catch crop in reducing nitrate leaching losses after simulated winter grazing of a kale crop. The experiment compared plant N uptake and nitrate leaching losses from a urine patch under several combinations of timing of urine deposition and the interval between urine deposition and sowing of the catch crop. Our hypothesis is that sowing a catch crop after urine application from winter forage grazing will reduce nitrate leaching losses and that this is enhanced the sooner the catch crop is sown.

Materials and Methods

Soil and lysimeter collection

The study was conducted using a Balmoral stony silt loam soil (Acidic Orthic Brown soil) collected from Lincoln University's Ashley Dene research farm situated near Springston (NZGD2000: 43 38 42S 172 20 33E) on the Canterbury Plains. Soil texture in the first 15 cm of each lysimeter profile was silt loam, but the soil profile became increasingly stony below this depth with ~50% of the soil volume occupied by stone by 30 cm and the remaining volume interspersed with fine-to-coarse sands. The soil initially supported established pasture consisting of a mixture of perennial ryegrass (*Lolium perenne* L., cultivar Grasslands Nui) and white clover (*Trifolium repens* L., cultivar Grasslands Huia). Forty-eight monolith lysimeters, 500 mm in diameter and 700 mm deep, were collected from the site in February 2014 (late summer). Some of the basic soil chemical and physical properties are presented in Table 1. Lysimeter collection followed the procedure described by Cameron et al. (1992). The installation of a gravel layer at the base of each lysimeter reproduced a situation common to the Canterbury Plains where soils often overlie coarse gravels. The gravel layer also allowed a free drainage system to be used in the lysimeter study, as matric potential in this layer was assumed to be zero (Clothier *et al.*, 1977). The lysimeters were moved to a purpose-built field trench at Lincoln University where the top of each lysimeter was flush with the surface of the soil surrounding it. This ensured that the lysimeters were exposed to the same environmental conditions as the rest of the field.

Treatments

After the lysimeters had been installed, the pasture vegetation was sprayed out with herbicide, and the soil surface was lightly cultivated by hand a fortnight later. Three, 3-month old forage kale (cultivar Regal) plants were transplanted into each lysimeter in early February, giving a plant population of ~16 plants/m^2. Basal nitrogen (equivalent to 40 kg N/ha, supplied as urea), phosphorus (15.4 kg P/ha; supplied as 15% potassic superphosphate), potassium (15 kg K/ha) and sulphur (18.4 kg S/ha) were applied after transplantation to help establish the plants. The kale was allowed to grow until winter when it was harvested to simulate grazing. Once the kale plants had been cut, the soil surface was “pugged” using a manually operated trampling device, designed to provide c. 200 kPa, and similar to that of the mechanical hoof described by Di *et al.* (2001). This simulated the impact of animal grazing on the soil surface under typical WFG conditions.

Treatments were based on different combinations of the timing of winter urine application, and the interval between urine deposition and the sowing of the catch crop. Three different urine application times spanning early- to mid-winter (early June, early July and late July) were chosen to represent the eight week period over which WFG typically occurs in Canterbury. Oats (cultivar Milton) catch crop treatments were sown within 1-3 days after each urine application event, and then nominally at 21 day intervals (Table 2). Sowing dates were reduced from four for the first urine application (nominally 1, 21, 42 and 63 days) to two (nominally 1 and 21 days) by the third so the final sowing occurred at approximately the same time (mid-August) for each urine application date treatment. Each treatment combination (n=4, including three control (fallow) treatments that received urine but were left unsown; Table 2) was replicated 4 times. Problems with rodent damage to seeds and germinated seedlings caused the early July (2nd application)– 21 day sowing treatment combination to be removed from the analysis.

Table 1. Selected soil chemical (0-75 mm) and physical properties for the Balmoral soil from the field site where the lysimeters were sourced.

Property	Value	Soil depth	SBD[1]	Stone vol.	Porosity	Texture[2]
pH	6.1	mm	g cm^{-3}	%	%	
Olsen-P	33 μg ml^{-1}	0-100	1.14	11	58	stony ZL
Exch-Ca	8.1 cmol$^+$ kg^{-1}	100-200	1.57	30	42	stony ZL
Exch-Mg	0.5 cmol$^+$ kg^{-1}	200-300	1.90	51	29	stony SL
Exch-K	0.4 cmol$^+$ kg^{-1}	300-400	2.05	54	24	stony S
Exch-Na	0.2 cmol$^+$ kg^{-1}	400-600	1.96	51	27	gravelly S
CEC	16 cmol kg^{-1}					
Reserve-K	3.6 cmol kg^{-1}					
Sulphate-S	4 μg g^{-1}					
Organic-C	45 g kg^{-1}					
Total-N	4.0 g kg^{-1}					
Organic-S	5 μg g^{-1}					
Base saturation	65%					

[1]soil bulk density; [2]ZL -silt loam; SL -sandy loam; S –sand

Urine was collected from non-lactating cows grazing on forage kale at the Ashley Dene farm and was applied to the lysimeters at a rate equivalent to 350 kg N/ha. This rate was based on analysis of total urinary-N content of urine from winter kale-fed cows and, due to the kale’s lower N content, is considerably lower than in urine from cows fed on pasture (Edwards *et al.*, 2014a). The urine was applied to each lysimeter in 2 L volumes, similar to the typical urination volumes of cows grazing on winter forage crops (Ravera *et al.*, 2015). The urine was analysed for total-N content immediately following collection and refrigerated overnight. The urine was poured rapidly on to the surface of each lysimeter to simulate an urination event.

Prior to sowing the oats, the soil surface was lightly worked to a depth of 5 cm and the seed sown by hand at a rate equivalent to 120 kg/ha. Lysimeters were left exposed to all natural rainfall over the 2014 winter with no artificial watering through this period until the oats were harvested in late spring (November 3). Irrigation water was applied from November 7 to mid-December to bridge the rainfall deficit and produce an average annual amount of drainage (~260 mm) for a Canterbury well-drained stony soil under irrigation (Lilburne *et al.*, 2010). Irrigation was automated to apply water in 0.5 mm increments over several hours to ensure leaching was largely conducted under unsaturated conditions.

Table 2. Urine application dates to lysimeters and post-application oats crop sowing dates. Fallow treatments received urine only.

	Urine application date		
	June 5	July 5	July 25
	Fallow	Fallow	Fallow
	1 day (Jun 6)	-	-
Oat crop sowing dates	22 days (Jun 27)	2 days (Jul 7)	-
	43 days (Jul 18)	[a] 25 days (Jul 21)	3 days (Jul 28)
	64 days (Aug 8)	44 days (Aug 11)	24 days (Aug 18)

[a] *Removed due to rodent damage.*

Measurements and data analysis

Climate and rainfall data were collected from the Broadfields meteorological station 5 km from the trial site and compared with long-term means (1980-2014). Drainage values were compared with the modelled range for light-to-very-light (i.e. stony) irrigated soils from actual lysimeter drainage data collected over a 10-year period in Canterbury (Lilburne et al., 2010).

Leachate from each lysimeter was collected and the volume measured after every significant rainfall event and/or once a volume of more than 0.2 L was present. A sub-sample of leachate was frozen until it was analysed for nitrate and ammonium (NH_4^+-N and NO_3^--N) concentrations by flow injection analysis (FIA) (Tecator, Sweden). Analysis of leachates showed they contained little or no organic-N (<4% of total-N on average) and thus no data is reported. After the oats were harvested they were dried in a fan-forced oven at 60° C before weighing and ground to pass through a Retsch cyclonic mill (<0.5 mm mesh). A sub-sample was analysed and measured for plant N content using an Elementar Vario-Max CN Elemental Analyser (Germany).

Total NH_4^+-N and NO_3^--N leaching losses were calculated as the product of their concentration in the leachate and the volume of leachate. Average annual leaching losses were then calculated using values from the four replicates. Statistical analysis was done using both balanced (sowing dates within an application) and unbalanced (across all application dates)

ANOVA within the Genstat 9.2 statistical package (VSN International Ltd., 2005). Duncan's multiple range test was used for comparisons between sowing days for individual urine application dates. Least significant differences (LSD) were calculated for multi-treatment comparisons.

Results

Climate and drainage

Air and soil temperatures during June 2014, in particular, were higher than the long-term average, but only slightly so in July and close to the average thereafter (Figure 1). Rainfall in spring was below the long-term average, especially in the period from August to October (Figure 1). Consequently, drainage over the same period was low at 75, 42 and 19 mm for the early, mid and late urine applications, respectively. More than half of the drainage for the early urine application was in the six week period following application. A further ~200 mm drainage was collected in the simulated rainfall period after November 7, bringing the total drainage for each treatment closer to the district average.

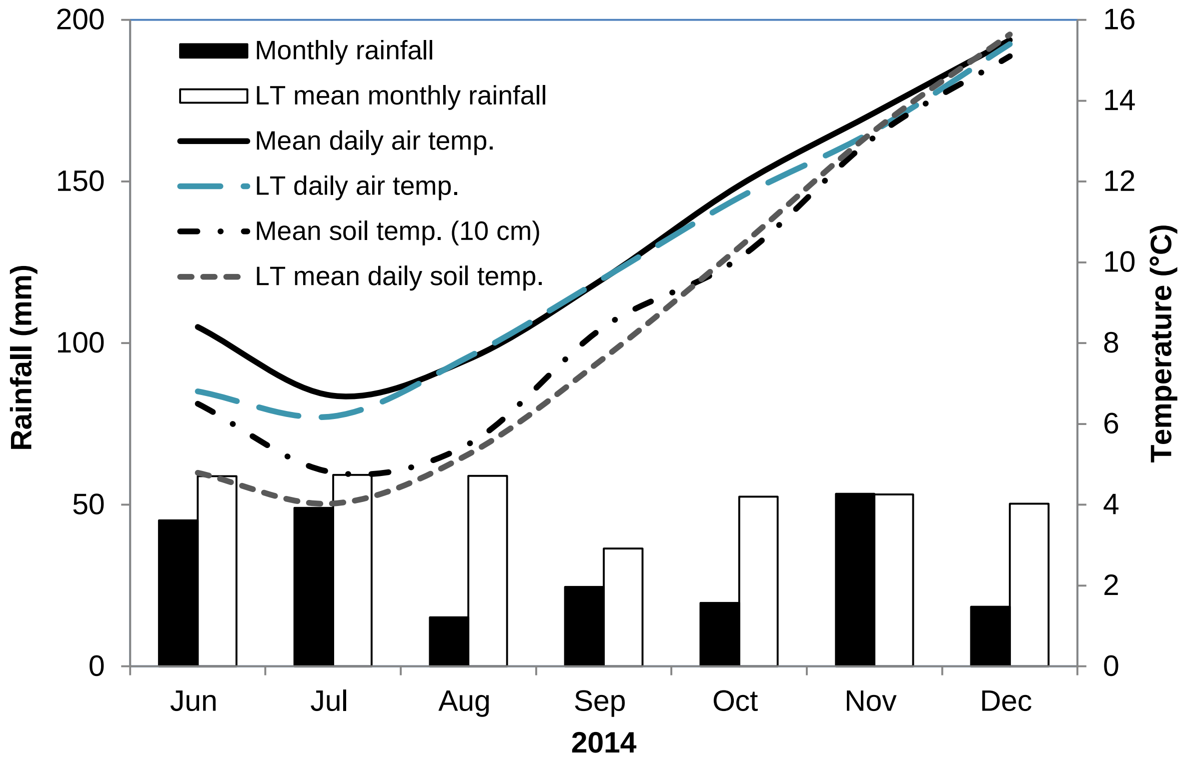

Figure 1. Mean Lincoln monthly rainfall, air and soil (10 cm) temperature recorded during winter-spring 2014 compared with long-term (LT) means (1980-2014).

Nitrate leaching loss and crop N uptake

Breakthrough curves (BTC) for NO_3^--N concentrations for the fallow treatments of the early, mid and late timing urine application treatments peaked at around 230, 180 and 130 mg N/L respectively. N concentrations declined to low levels after about 300 mm of drainage (Figure 2). Nitrate comprised almost the entire amount of N leached, apart from a small amount of ammonium leached initially after the early urine application (<3% of total-N leached). Nitrogen leaching losses for the winter-spring drainage period were significantly different between urine application dates (P<0.001) at 272, 224 and 172 kg N/ha for early, mid and late fallow treatments, respectively (Figure 3).

The presence of a catch crop reduced N concentrations in the leachate by 20-60% (Figure 2) compared with the fallow treatments. The catch crop significantly reduced (P<0.001) nitrate leaching loss by between 19-49% and by ~34% on average for all treatments over the drainage period (Figure 3). A catch crop sown between 42 and 63 days after urine application in early winter reduced N loss on average by 30%. Nitrate leaching losses generally increased with later sowing of the oats although differences between early and later sowing dates were not significant overall (Figure 3).

There was a statistically significant effect of the interval between urine deposition and sowing of the catch crop on total oats DM harvested (P<0.001), and on total plant N uptake by the oats (P<0.05). In general, the sooner the oats were sown after the urine was applied, the greater the amount of DM harvested and N taken up by the crop as shown particularly by the sowing dates for the early urine application (Figure 4). However, N dilution within the plants for those crops sown earlier compared with those sown later meant differences in total crop N uptake were less pronounced than for DM (Figure 4). Consequently, differences in catch crop N uptake were only significant between the day 1 and day 42 sowing dates for the early urine application and were similar overall (~70 kg N/ha) between early, mid and late urine applications. Drainage volumes were generally least for the earliest oats sowing date for each of the urine applications compared to the corresponding fallow treatment (all approximately 260 mm) and/or later sown treatments (P<0.001; Figure 3).

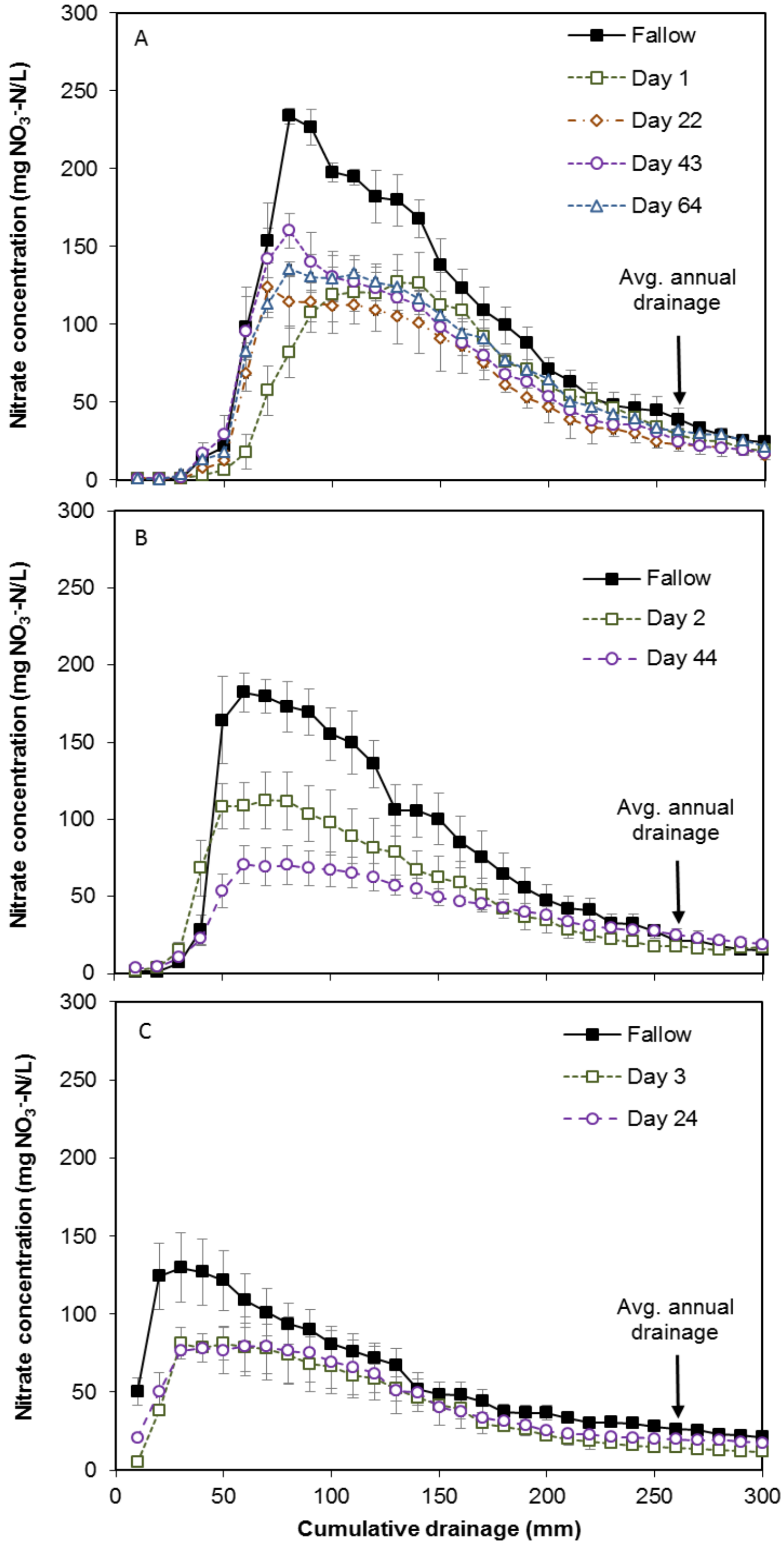

Figure 2. Nitrate leaching breakthrough curves (and standard errors) for fallow and catch crop treatments for A) early, B) mid and C) late urine applications (equivalent to 350 kg N/ha). Crops were sown approximately 2, 23, 44 or 64 days after urine application. Annual average drainage for an irrigated Balmoral soil in district is shown for each graph (Lilburne et al., 2010).

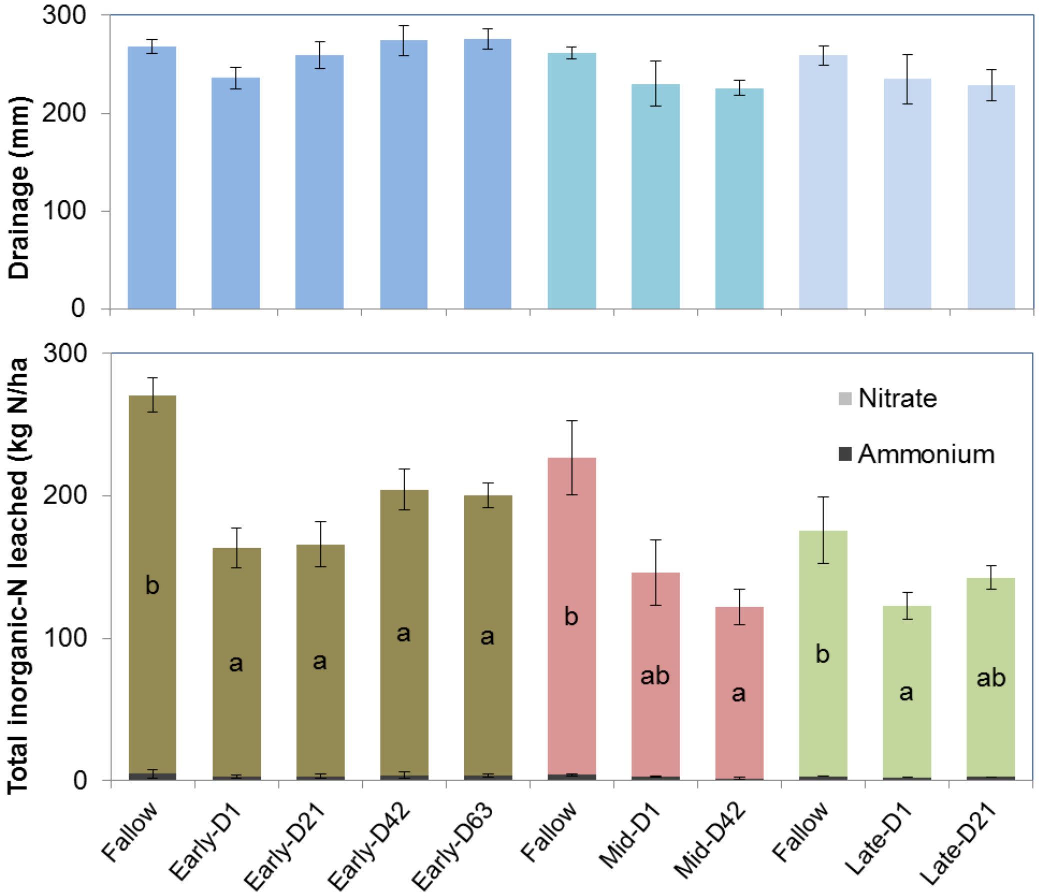

Figure 3. **Total N (NH_4^+-N & NO_3^--N) leached and drainage volumes for each urine application (early- June 5, mid- July 5 and late- July 25) and sowing date (day 1–day 63). Standard error bars shown. Letters not in common denote significance at P<0.05 according to Duncan's multiple range test.**

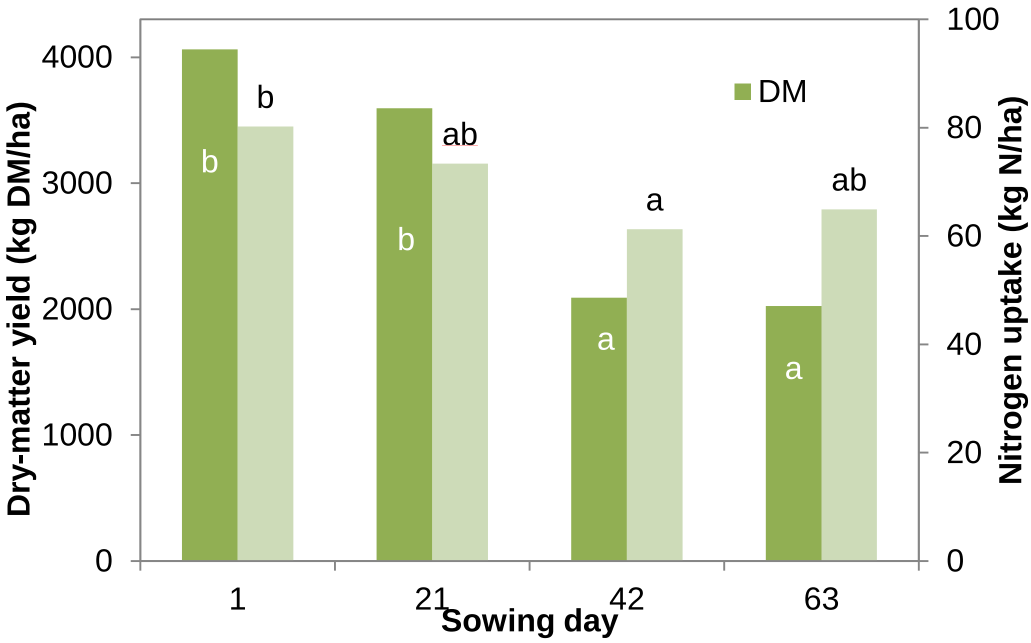

Figure 4. **Dry-matter production and N uptake for each sowing date for the early urine application (June 5). Letters not in common between treatments denote significant differences at P<0.05.**

Discussion

Nitrate leaching and N uptake

Sowing oats as a catch crop following urine application after simulated winter forage grazing reduced nitrate leaching losses by ~34% over all treatments compared with the fallow treatments (range 19-49%). In the critical 42-63 day period after winter forage grazing, when soil conditions might be more favourable to sowing a catch crop, N loss was reduced by ~30%. These values are similar to those reported by Francis *et al.* (1995) who found an average 30% reduction in N loss from autumn sown green feed oats in a conventional catch crop of autumn sown green feed oats, following ploughing in of a 4-year old Canterbury ryegrass/white clover pasture.

The oats sown soon after the early winter (June) urine application yielded about twice as much total DM at time of harvest as the later-sown treatments. Nitrogen uptake of around 60-80 kg N ha^{-1} covered all treatment combinations so despite a large difference in DM production, there was less effect on N uptake with significant N dilution occurring within the plants from the earlier sown oats. Low drainage over the period probably contributed to this reduced range as more rainfall, post-winter forage grazing, over the mid-to-late winter period, would have increased nitrate leaching and reduced N uptake for later sowing dates. Francis (1995) found that an oats catch crop with a yield of about 3 tonnes ha^{-1} sown in autumn contained 80 kg N ha^{-1}, similar to the maximum in our study.

Normal practice, post-winter forage grazing, is to sow the land back into pasture or kale in the spring, but this may be up to three months after the final grazing, so the potential for large nitrate leaching losses from high soil mineral-N concentrations is considerable. Currently, there is little field data on soil mineral N concentrations post-winter forage grazing in Canterbury but Francis (1995) found that where an autumn-sown leguminous cover crop had been lightly grazed over the winter, soil mineral-N concentrations (to 600 mm depth) were much higher in the spring compared to when a catch crop had been incorporated (62-164 kg N/ha vs. 19-44 kg N/ha^{-1}, respectively). The rate of mineralisation of urinary-N over winter and early spring, in comparison with a green manure, means forage grazing over this period needs a strategy, such as a catch crop, to decrease soil mineral N concentrations to avoid large nitrate leaching losses.

The early planting of a catch crop like oats offers a strategy to reduce N losses from winter forage grazing systems but it will depend on the prevailing climatic conditions, soil type, rainfall distribution and the speed of crop establishment. For instance, Francis *et al.* (1998) found sowing a range of catch crops in Canterbury in March achieved DM production of 1440-3100 kg ha^{-1} by the start of winter but sowing in April, one month later, resulted in very little. In our study, warmer than average air and soil temperatures for the oats sown in June meant these established well initially, providing a good start for later growth when temperatures warmed again. There are differences, however, between using catch crops in arable mixed cropping sequences with their use in winter forage grazing systems. For example, incorporation of pasture means a potential build-up in soil mineral-N at deeper depths (>400 mm) whereas urine may remain close to the surface during winter forage grazing, at least initially.

Currently, there is no published information available on the use of catch crops to capture N post-winter forage grazing; most New Zealand studies report the use of crops in more conventional mixed cropping-pasture sequences. Comparison with catch crop studies conducted in other countries is not possible since the crop is sown after the harvesting of a summer crop to capture residual soil N for a following spring-sown crop (Thorup-Kristensen *et al.*, 2003) and their harsher winter conditions mean most dairy cattle are housed inside over the winter (Hopkins, 2008).

Although N uptake from the soil is the primary benefit of sowing a catch crop, there is an indirect benefit on nitrate leaching of reduced drainage because there is an evaporative water loss from the growing crop that exceeds surface soil evaporation alone. However, Francis (1995) and Francis *et al.* (1998) found that drainage in catch crop treatments was only lower than the fallow (ploughed pasture) treatment when the crops were sown in early autumn, giving them time to establish. This indicates a strong dependence on climatic variables, and urine-N applied in winter forage grazing in early winter is likely to be at more risk from leaching than in late winter/spring onwards, when conditions are more optimal for crop growth (Teixeira *et al.*, 2016).

Factors affecting nitrate leaching

Despite low soil temperatures, the bulk of the urinary-N deposited directly to the soil surface during winter forage grazing will undergo rapid hydrolysis to ammonium within hours (Sherlock & Goh, 1984). Although some bypass or macropore flow of the urine can occur, the soil surface often becomes poached by stock trampling during winter forage grazing so there is less likelihood of macropore flow occurring prior to nitrification (Houlbrooke *et al.*, 2009). A proportion of ammonium will be lost to ammonia volatilisation but in winter this is likely to be a minor fraction (~12%; (Sherlock & Goh, 1984) so the bulk will interact with the soil cation exchange complex, awaiting nitrification (Haynes & Williams, 1993). The subsequent nitrification process is slowed, if not halted, at low winter temperatures (<5°C) (Flowers & Arnold, 1983; Cookson *et al.*, 2002) thus, it may take up several months before peak soil nitrate concentrations are reached (Holland & During, 1977). Depending on the prevailing winter conditions there may still be a sufficient window for a cool-season active crop like oats to assimilate significant quantities of N before declining temperatures reduce growth further. One effect of colder temperatures is to increase root N concentrations, especially in cereals and thus, early development of the catch crop root system is likely to be an important sink in storing some of the deposited urinary-N and protecting it against leaching (Laine *et al.*, 1994). Indeed, a winter wheat trial sown in Canterbury after pasture incorporation in May retained 55% of its total-N content (51 kg N ha^{-1}) in its roots by time of sampling in October (Francis et al., 1995).

The Balmoral soil used in the study is typical of land used for winter forage grazing in Canterbury, being mostly stony with a low water holding capacity (Cutler, 1968). Nitrate leaching loss in our study declined significantly with each progressively later urine application and this is largely attributed to the lack of rainfall after the early and late July applications, allowing the urinary-N to remain longer in the topsoil compared with the June application that was followed by significant rainfall. In addition, the longer the urinary-N remains in the biologically-active topsoil the greater the opportunity for immobilisation and denitrification to occur. Denitrification losses in particular are enhanced under compacted soil conditions where the oxygen supply is reduced and a source of labile carbon and a high nitrate concentration co-exist (Bolan *et al.*, 2004; Ball, 2013; Saggar *et al.*, 2013). Greater rainfall and drainage following the early-June urine application probably meant more urinary-N was leached below the biologically active topsoil, reducing the denitrification loss. In a field trial measuring nitrate leaching losses after winter forage grazing in the Waikato region of New Zealand, Carlson et al. (2013) also reported lower losses from a late-July compared with an early-June urine application (26 and 119 kg N/ha, respectively).

Paddock N losses

The relatively large nitrate leaching losses observed in this study relate to nitrate leaching directly under a urine patch (where the N loading is equivalent to 350 kg N/ha) and are not representative of losses at a paddock scale. Previous published (Malcolm et al., 2015) and unpublished work using this soil type in two similar lysimeter studies indicate N loss under a kale winter forage crop from non-urine affected areas is ~30-40 kg N/ha. This will, of course, vary to some degree depending on the prior history of the paddock plus any contributions from residual fertiliser-N and mineralisation of the previous pasture or crop. The paddock scale loss will depend on the actual area occupied by urine patches, which is always likely to be a fraction of the total grazed area (Jenkinson *et al.*, 2014). Currently, research is underway at Lincoln University to determine accurate estimates of the extent of urine coverage within a paddock post-grazing. Because of the high stocking rates on winter forage grazing land, the potential for large N leaching losses at the paddock scale remain high and there is clearly a need for mitigation measures, such as growing a catch crop. An advantage of the kale-oats catch crop system is the additional DM production from the oats which can be used as low-N feed for cows in the following winter. Edwards *et al.* (2014b) found DM production and N use efficiency increased by 40% and 29%, respectively, over kale alone, by inclusion of oats as a catch crop in the winter forage cropping system.

Practical issues remain around the timing of sowing of a catch crop and whilst sowing as early as possible is preferable, this will depend on the grazing management, climatic conditions and soil resistance. There is, therefore, a need for further data to predict the effectiveness of a winter sown cover crop on N leaching losses after winter forage grazing over a range of climatic and soil conditions.

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