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ORIGINAL ARTICLE

Oat catch crop efficacy on nitrogen leaching varies after forage crop grazing

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Abstract This study tested the effect of oat catch crops on mineral nitrogen (N) leaching losses from cool season fodder beet grazing. Undisturbed soil monolith lysimeters were collected from two grassland sites with soils featuring contrasting texture and water holding capacity (WHC) characteristics. After simulated fodder beet grazing in late autumn or winter, synthetic dairy cow urine was applied. Nitrogen leaching losses were measured from lysimeters sown with oats after urine application and compared with those under fallow conditions until spring. Oat dry matter (DM) production and N uptake measurements were obtained. Sowing oats reduced total mineral N leaching losses by up to 59%. Reductions in mineral N leaching were inconsistently affected by soil type but were strongly influenced by urine application timing. Nitrogen uptake by oats (52–143 kg N ha^{-1}) drove reductions in N leaching losses compared with fallow soil. Oats yielded 4–17 t DM ha^{-1}, and both yield and N uptake were strongly affected by urine application timing (winter > autumn) and soil type (high WHC > low WHC). Sowing oats after fodder beet grazing instead of leaving the ground fallow can reduce the environmental impacts of these systems, while simultaneously increasing annual feed supply. Catch crop gains can be maximised by avoiding or delaying autumn grazing of fodder beet, particularly on low WHC soils.

Keywords Nitrate leaching · Cover crop · *Avena sativa* · *Beta vulgaris* L. ssp. *vulgaris* var. *alba* · Winter grazing · Forage crop

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Introduction

In New Zealand, large amounts of urinary nitrogen (N) are excreted onto bare soil during livestock grazing of high-yielding forage crops such as fodder beet (*Beta vulgaris* L. ssp. *vulgaris* var. *alba*) and kale (*Brassica oleracea* var. *acephala* L.) (Edwards et al.

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2014; Ravera et al. 2015). This N is highly susceptible to leaching because grazing often coincides with the late autumn/winter period which is commonly followed by a fallow period of up to five months where there is no plant demand for N until a new crop is re-sown in spring. This is further exacerbated by typically high rates of drainage during winter and early spring as a result of high rainfall and low evapotranspiration (Cameron et al. 2013; Selbie et al. 2015). Importantly, N leaching can result in detrimental effects to the environment, such as elevated nitrate (NO_3^-) in groundwater contributing to eutrophication of streams and lakes (Addiscott 1996; WHO 2007; Wild and Cameron 1980). Farmers in New Zealand are under increasing regulatory pressure to reduce their environmental footprints, and livestock grazing forage crops in autumn or winter offers a very cost-effective, high quality feed source (at a time when pasture growth rates are slow); therefore, mitigation technologies are required to reduce N leaching losses from grazed forage crops to ensure the sustainability of these grazing systems in future.

Catch crops are a specific type of cover crop established between two main crops that target the capture of residual soil N to reduce the risk of N leaching. Catch crops have traditionally been sown in arable systems following a summer crop and before the onset of winter rainfall where they can significantly reduce N leaching losses (Francis et al. 1995; Fraser et al. 2013; Gabriel et al. 2012; Meisinger and Ricigliano 2017; Teixeira et al. 2016; Thapa et al. 2018; Walmsley et al. 2018). In a meta-analysis of the effect of *cover crops* in agroecosystems, Thapa et al. (2018) identified that NO_3^- leaching was on average 56% lower when non-leguminous species were grown compared with that under fallow soil conditions. Cover crops were also shown to be more effective in coarse-textured soils than in fine-textured soils. The reduction in NO_3^- leaching under catch crops has been attributed to removal of soil mineral N, a reduction in soil water drainage (due to greater evapotranspiration) and increased soil microbial immobilization stimulated by carbon exudates from plant roots (Carey et al. 2018; Kuzyakov and Domanski 2000; Rees et al. 2005).

Recent research in New Zealand has investigated the extent to which winter-sown oat (*Avena sativa*) catch crops can assimilate N from urine deposited by grazing animals on winter forages and reduce the risk of NO_3^- leaching (Carey et al. 2016; 2017; 2018; Malcolm et al. 2016b, 2017, 2018, 2021). Using soil monolith lysimeters consisting of stony Balmoral silt loam, Carey et al. (2016) showed that NO_3^- leaching losses from livestock urine during a relatively dry winter-spring period were reduced by up to 49% compared with those of fallow soil when oats were sown in winter (June or July). Carey et al. (2018) further demonstrated significant reductions in NO_3^- leaching under oats grown at constant air temperatures of either 6 or 10 °C, and identified a window of opportunity created by slower rates of nitrification in periods of cooler temperatures during which catch crops can capture N before it is leached. However, important knowledge gaps remain about the influence of soil type/texture and the timing of urine deposition in late autumn–winter on the effectiveness of catch crops following grazed forage crops.

The objectives of this study were to: (i) test the effect of winter sowing date of an oat catch crop and soil type on yield, N uptake and mineral-N leaching losses after simulated winter forage crop grazing, and (ii) determine the effect of urine application timing (autumn vs winter forage crop grazing), on the performance of oat catch crops, using soil monolith lysimeters. We hypothesised that catch crops would be most effective when sown early on coarse-textured soils, given N leaching losses are likely to be higher than those of finer-texture. We also hypothesised that catch crops would be most effective following autumn-grazed forages compared with those grazed in winter, because soil temperatures are likely to be warmer when the catch crops are establishing, and the growing window is longer.

Materials and methods

Lysimeter collection, pre-treatment management and irrigation.

In early 2017 a total of 32 undisturbed soil monolith lysimeters (500 mm diameter and 700 mm deep) were collected from two grassland sites (16 monoliths at each site) in Canterbury, New Zealand, representing two different soil textures. The first site was at Lincoln University's Ashley Dene Research and Development Station near Lincoln, Canterbury (−43° 38.7′, 172° 20.7′; 17 m asl), which had previously been in permanent pasture for approximately 20 years. The soil was a free-draining Balmoral stony silt loam [Acidic Orthic Brown Soil (Landcare Research 2016); Typic Dystrudept (Soil Survey Staff 2014)], characterised by a very stony silt loam topsoil overlying very stony sandy subsoils (Carrick et al. 2017) and low water-holding capacity (WHC). Such stony soils, developed from gravelly glacial outwash materials covered with varying depths of loess, are widespread on the Canterbury Plains and extensively used for irrigated dairy farming (Carrick et al. 2013). The second site was also located near Lincoln (−43° 37.9′, 172° 27.4′, 17 m asl), but was a Templeton silt loam [Immature Pallic soils (Hewitt 2021); Udic Ustochrept (Soil Survey Staff 2014) with high WHC], formed in stone-free hard sandstone derived alluvial sediments, with defining soil features of being well drained with silt loam texture grading from sandy loam to sand texture below 400–600 mm depth (Cox 1978). Previously, the site had been under ryegrass pasture for approximately three years, and under long-term cropping before that. For a detailed description of the soil texture and chemical properties in the top 200 mm, refer to Thomas et al. (2019). Both soils are commonly found across the Canterbury landscape, and are extensively used for forage crop grazing.

The lysimeters were collected using the methods described in Cameron et al. (1992). In brief, this involved placing a metal cylinder on the soil surface, carefully digging the soil from around the cylinder, and by small increments, pushing the cylinder into the soil until the top was 5 mm above the soil surface. The 5 mm of casing remaining above the soil surface prevented runoff into or out of the lysimeter during the trial. The soil monoliths were then cut off at the base using a hydraulically operated cutting plate, which was subsequently secured to the base of the cylinder. Petroleum jelly was then injected into the annular gap that was created between the soil core and the cylinder to prevent preferential edge-flow. Lysimeters were then carefully inverted and approximately 50 mm of soil at the base of each lysimeter was replaced with coarse gravel to ensure drainage water would pass without restriction.

The lysimeters from both field sites were installed into a field trench facility at the Lincoln University Research Dairy Farm (LURDF), Lincoln (−43° 38.4′, 172° 27.4′) so that the soil surface of each lysimeter was at the same level as the surface of the surrounding field. The space outside the lysimeters was backfilled with soil to the same level as the soil surface of the lysimeters. Plastic tubing was connected to the base of each lysimeter, which fed drainage water into 10-L collection vessels.

In early autumn of 2017 and 2018, pasture herbage inside the lysimeters was sprayed with glyphosate. When senescence had occurred, six-month-old fodder beet (cultivar 'Rivage') plants were transplanted into each lysimeter with minimal soil disturbance at a density of two plants per lysimeter (Malcolm et al. 2019). This represented the recommended commercial target plant population of 8–10 plants m^{-2} (Chakwizira et al. 2014; Matthew et al. 2011). Weed growth on the fallow lysimeters was controlled with targeted application of glyphosate. Other agrichemicals and nutrients were applied as per normal farm practice, and to ensure no nutrient deficiencies (full details given in Supplementary Table 1). While it should be noted that transplanting fodder beet at this maturity stage does not represent industry practice, this was necessary to fit within necessary time frames. Of critical importance was that lysimeters were managed equally leading up to the beginning of experimentation.

From the time of initial treatment applications until October, rainfall was supplemented (if and when required) by irrigation to all lysimeters at rates sufficient to ensure total water inputs were equivalent to at least the 75th percentile of mean total monthly rainfall for Lincoln (calculated from the 25-year period between the beginning of 1975 and the end of 1999) through simulated rainfall events randomly generated to meet daily target levels (Malcolm 2013). Thereafter, summer irrigation was applied at regular rates and time intervals to match normal farm practice in the Canterbury region. Water was applied through a fully automated irrigation system consisting of TeeJet® FL-5VC spray nozzles mounted directly over the top of each lysimeter. Air temperature and rainfall during the trial period was recorded by an on-site climate weather station.

Experimental design and treatment application

The same lysimeters were used to quantify NO_3^--N and ammonium-N (NH_4^+-N) leaching losses under different experimental treatments over two independently run experiments; the first in 2017 (Experiment 1; hereafter 'Exp. 1') and the second in 2018

(Experiment 2; hereafter 'Exp. 2'). Residual soil mineral N remaining after Exp. 1, i.e. after drainage had ceased, was flushed from all lysimeters over a six-week period in early 2018 using irrigation (approx. 600 mm) before transplanting fodder beet crops in preparation for Exp. 2. This flushing process was important to ensure background N concentrations in drainage were achieved before Exp. 2 commenced. To further minimise potential carry-over effects from Exp. 1 treatments, Exp. 2 treatment replicates were assigned one of each of the treatment replicates from Exp. 1, within the same soil type.

Experiment 1 (sowing timing and soil type effects)

Factors consisted of urine application (with or without, representing urine and non-urine areas of a paddock), catch crop sowing timing and soil type. The lysimeters were arranged in a randomised block design, consisting of eight treatments and four replicate blocks (Supplementary Table 1). On 6 July 2017 all fodder beet plants (bulb and green material together) were pulled and removed from the lysimeters to simulate a winter grazing event (weights were not recorded) (Malcolm et al. 2016a, 2019). To further simulate grazing, the surface inside each lysimeter was then "trampled" using a manually operated trampling device as described in Malcolm et al. (2015), to mimic the walking action of cow hooves. Visually, the soil surface represented that of a trampled soil following grazing at a typically high stocking density.

All lysimeters, except for the nil-urine treatments, received 2 L of synthetic cow urine on the day following simulated grazing, at an N loading rate equivalent to 300 kg N ha^{-1}. The synthetic cow urine was made up to represent natural urine from cows fed on a fodder beet diet, and contained urea, glycine, potassium bicarbonate, potassium chloride and potassium sulphate (Clough et al. 1998; Edwards et al. 2014).

Two catch crop sowing date treatments were tested against a fallow control for each soil type (Supplementary Table 1). Oats were sown by hand to mimic a direct drill, which involved creating 30-mm deep slots at 150-mm row spacings across the lysimeters, placing seed inside the open slot at a seeding rate of 110 kg seed ha^{-1} (target population of 300 plants m^{-2}), and covering the slot over with soil. The fallow control treatments were managed as per common on-farm practice, which involved leaving the soil bare and sowing perennial ryegrass/white clover pasture in spring (Supplementary Table 1).

Experiment 2 (urine application timing and soil type effects)

Factors were grazing/urine application timing, catch crop (with or without) and soil type, and treatments were carried through beyond the catch crop phase in order to consider outcomes over the subsequent pasture phase (Supplementary Table 1). The lysimeters were arranged in a randomised block design, consisting of eight treatments and four replicate blocks (Supplementary Table 1). Four of the treatments tested in Exp. 1 (winter-applied urine with or without a catch crop, two soils types) were repeated in Exp. 2 for seasonal comparisons.

Simulated grazing (fodder beet removal and manual trampling) occurred on half the lysimeters on 3 May 2018 (autumn treatments), and the other half on 9 July 2018 (winter treatments), followed by urine application (Supplementary Table 1). Both simulated grazings and urine applications were carried out as per those in Exp. 1. All catch crops treatments were established within four days of urine application for both simulated grazing times (autumn and winter), using the same methods as per those in Exp. 1 (including fallow controls).

At the end of the catch crop phase (harvested November), lysimeters were immediately sown with perennial ryegrass/white clover. Perennial ryegrass/white clover pasture mixes consisted of 23 kg ha^{-1} 'Arrow' perennial ryegrass seed, 2 kg ha^{-1} 'Apex' white clover and 2 kg ha^{-1} 'Weka' white clover seed, and were seeded using the same procedure as that used for the oats, but at 750-mm row spacing.

Leaching and crop measurements

In Exp. 1, measurements commenced after winter urine applications on 7 July, and ceased on 8 December 2017 (Supplementary Table 1). In Exp. 2, measurements began after initial autumn urine applications on 4 May 2018, and ceased approximately 12 months after the urine application (Supplementary Table 1).

Leachate collection

Drainage water from the lysimeters was collected when the volume of drainage reached approximately 2–4 L. Total drainage volume was measured and subsamples were analysed for NO_3^--N and NH_4^+-N by flow injection analysis (FIA) (Gal et al. 2004; Tecator Inc., Sweden). The total amount of mineral N (NO_3^--N + NH_4^+-N) leaching loss at each sampling occasion was calculated from mineral N concentrations in the drainage water from each lysimeter and the volume of drainage water. Mean mineral N leaching losses per hectare were then calculated as means of the accumulated mineral N losses from four replicate lysimeters.

Biomass production and nitrogen uptake

Aboveground biomass of oat catch crop treatments was harvested at ground level at approximately green-chop silage maturity (approx. 50% panicle emergence), as indicated in Supplementary Table 1. Additionally, in Exp. 2 perennial ryegrass/white clover pasture was cut to a height of 50 mm (a typical post-grazing height in New Zealand) on a monthly basis, to simulate normal rotational grazing practice in New Zealand dairy systems. Only a single pasture cut was obtained in Exp. 1 (at the end of the experiment). Subsamples of cut herbage were oven-dried at 60 °C for 48 h (or until a constant weight was achieved), and dry matter (DM) production was determined. Dried samples were finely ground using a Cyclone Sample Mill (Udy Corporation, Fort Collins, Colorado, USA) to pass through a 1-mm screen, and analysed for total N concentration using an Elementar Vario-Max CN Elemental Analyser (Elementar GmbH, Hanau, Germany). Nitrogen uptake was calculated based on DM yield and average herbage N concentration.

On 1 October 2017 (Exp. 1), a mob of calves unexpectedly entered the trial area and consumed all biomass growing inside the lysimeters to ground level; no evidence of dung or urine returns to the lysimeters was observed. Consequently, we used historical N uptake data from two previous oat catch crop field trials to estimate N uptake by the catch crop from sowing up until the point of grazing by the calves (details provided in Supplementary Information); thereafter measurements were conducted on the regrowth material.

Statistical analysis

Data were analysed using a mixed model approach, fitted with REML as implemented in Genstat (Genstat 17th edition). For Exp. 1, for both the explanatory variables leaching and biomass, not all combinations of crop type and urine treatments were tested. For these variables, instead of looking at the main effects and interactions of crop type and urine treatment, we looked at a combined treatment effect (the interactions of the levels present). Fixed effects in the model were soil type, crop/urine and its interaction. For Exp. 2, fixed effects in the model were soil type, grazing time, crop type and all interactions. The random effect for both experiments accounted for the position of the lysimeter (block). For catch crop N content in Exp. 1 a nested random effect of crop within block was included. Model assumptions were checked via standard residual plots and log transformation applied when needed. All dates assessed were analysed separately, as independent measurements.

Results

Rainfall and air temperature

Totals of 506 and 1322 mm of water were received during the measurement period in Exp.'s 1 and 2, respectively, of which approximately 50% was through simulated rainfall/irrigation (Figs. 1a, c). Winter/early spring months were wetter than the long-term averages (1971–2000). During the months of July to September 2017, monthly water inputs (largely natural rainfall) were on average 43 mm higher than long-term rainfall trends (Fig. 1a). In Exp. 2, total monthly water inputs from May to September were 24 mm higher than the long-term mean (Fig. 1b). Overall daily mean air temperatures were similar to long-term district averages during the measurement period in both experiments (Figs. 1b, d). However, during the winter/spring periods, temperatures were, on average, about 1.0 and 0.6 °C warmer than the long-term means.

Nitrogen leaching losses and drainage

Mineral N concentration in drainage water (mg N L^{-1}) and cumulative N leached (kg N ha^{-1}) following

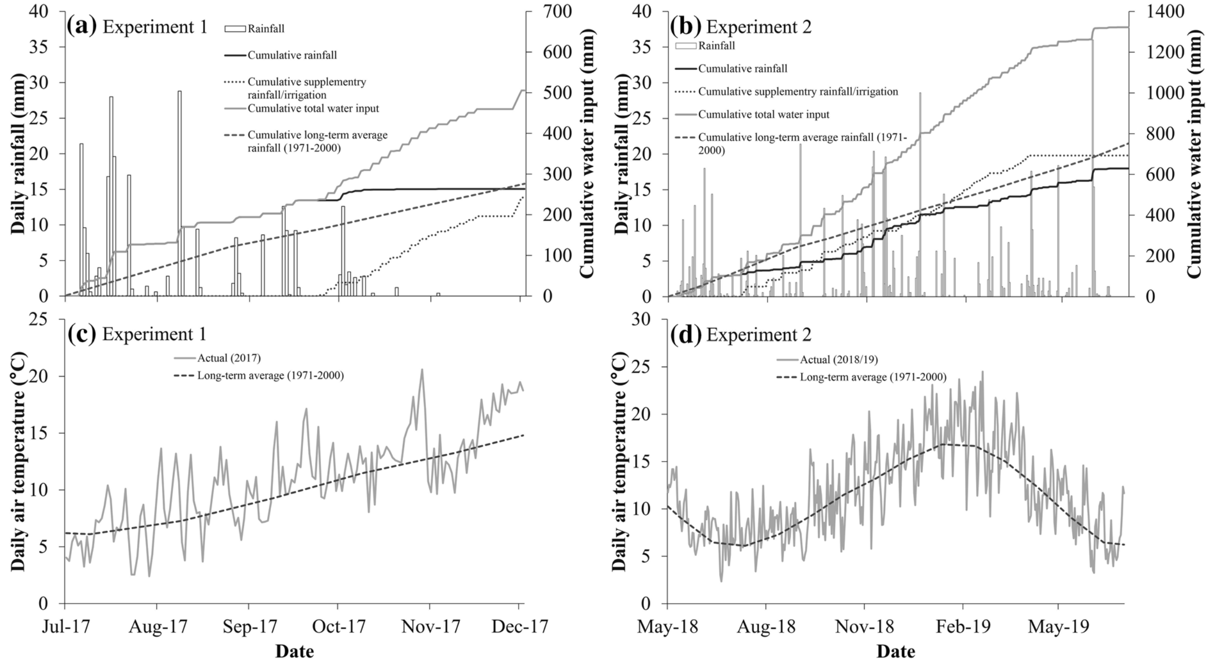

Fig. 1 Climate and water input data for the catch crop soil monolith lysimeter experiments, Lincoln, New Zealand. Daily rainfall, cumulative rainfall, cumulative supplementary irrigation, cumulative water input and cumulative 30-year district normal rainfall are given for **a** Experiment 1 (2017), and **b** Experiment 2 (2018–2019). Daily average air temperature and 30-year district normal temperature is given for **c** Experiment 1, and **d** Experiment 2

treatment applications in Exp.'s 1 and 2 are given in Figs. 2 and 3, respectively. In both experiments, 89–100% and 99–100% of mineral N leached was NO_3^--N for the Balmoral and Templeton soil treatments, respectively (data not shown).

Experiment 1 (sowing timing and soil type effects)

For the Balmoral soil treatments, mineral N concentration in drainage water peaked at between 189 and 235 mm of cumulative drainage (Fig. 2a). The application of urine resulted in higher peak N concentrations (153–177 mg N L^{-1}) than in the nil-urine fallow treatment (41 mg N L^{-1}) (Fig. 2a). Differences in peak N concentration between + urine treatments were minimal, but oats caused N concentrations to decline earlier than the fallow urine treatment, particularly for the July-sown oats treatment. Mineral N concentrations in drainage water from the Templeton soil were lower than those of Balmoral soil treatments, with concentrations of urine treatments reaching a maximum of 69–101 mg N L^{-1} in 206–260 mm of cumulative drainage. Total cumulative N leaching losses by the end of the measurement period (December) were highest in the fallow urine treatments for both soil types (224 and 79 kg N ha^{-1} under Balmoral and Templeton soils, respectively) (Fig. 2). Catch crops sown in July and August significantly ($P < 0.05$) reduced total N leaching losses from the Balmoral soil by 46% and 32%, respectively, with reductions becoming apparent from mid-September (Fig. 2c). For Templeton soil treatments, reductions were smaller (9–19% lower under the oat catch crop compared with the fallow treatment), and statistically not significant.

Total drainage collected from the lysimeters ranged from 221 to 315 mm (Fig. 2). The average amounts of drainage water at the end of the trial period in early December 2017 were significantly ($P > 0.05$) lower (by 17–22%) under July- (225 mm) and August- (239 mm) sown oat treatments compared with amounts in the fallow + urine control (289 mm) (Table 1).

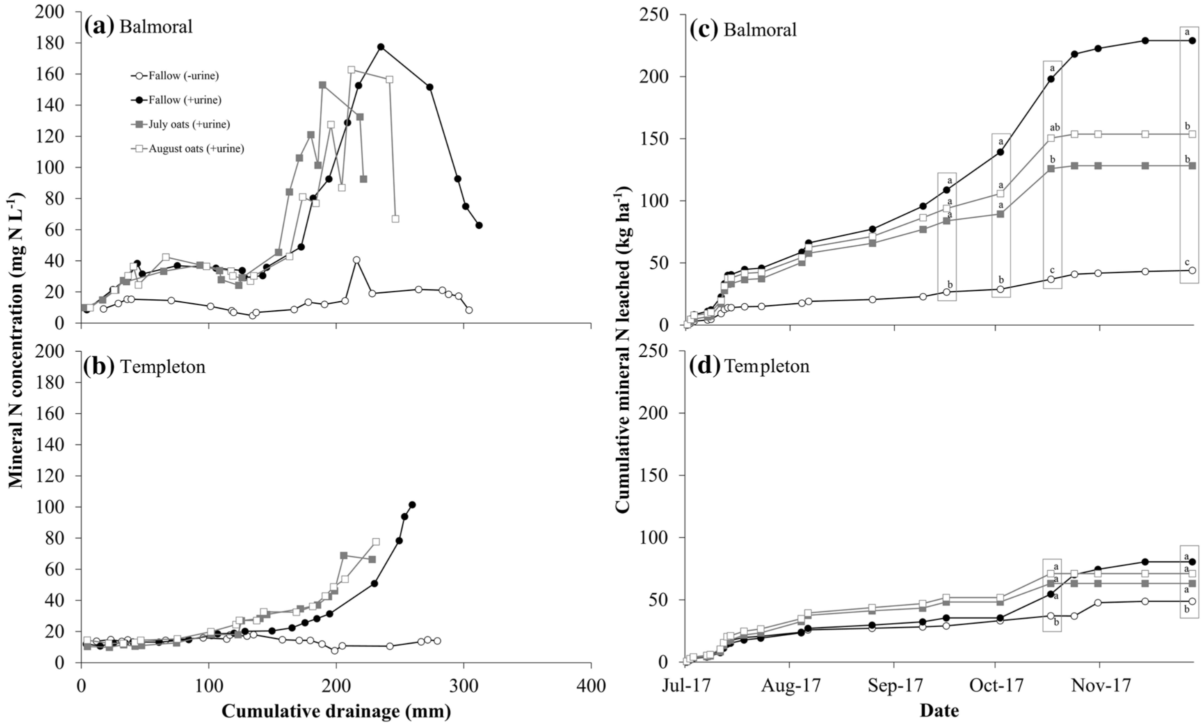

Fig. 2 Mean mineral N concentration (mg N L^{-1}) and cumulative mineral N leached (kg N ha^{-1}) in drainage water collected from monolith lysimeters after urine application (300 kg N ha^{-1}) in July of Experiment 1 (2017) on stony Balmoral silt loam (**a** and **c**, respectively), or Templeton silt loam (**b** and **d**, respectively). Different lower case letters on a given date (within boxes) indicate significant difference, according to the LSD/LSR (least significant difference/ratio; 5%)

Experiment 2 (urine application timing and soil type effects)

Mineral N concentrations peaked at approximately 195 mg N L^{-1} for autumn urine treatments, when 95 mm of cumulative drainage water had passed from the Balmoral soil lysimeters (Fig. 3a). For winter urine treatments on the same soil, peak concentrations were 159 mg N L^{-1} (fallow) and 124 mg N L^{-1} (oats), at which point approximately 225 mm of cumulative drainage water had passed. Peak N concentrations under Balmoral soil were observed earlier and at less cumulative drainage following autumn urine application than winter application. Oat catch crops were most effective at reducing mineral N concentration from winter-applied urine, which was apparent from early spring when approximately 200 mm of drainage water had passed. For Templeton soil, peak mineral N concentrations reached approximately 110 and 70–80 mg N L^{-1} for autumn and winter urine applications, respectively, and were observed earlier under autumn urine applications than under winter urine (Fig. 3b). Overall the emergence of peak N concentrations was delayed under Templeton soil compared with that under Balmoral soil. Sowing oats in May resulted in lower N concentrations by c. 6–33 mg N L^{-1} from about 240 mm of cumulative drainage compared with the fallow control, while when oats were sown in winter, reductions in N concentration of 5–80 mg N L^{-1} were observed from about 280 mm of cumulative drainage (when accounting for drainage before winter urine application, i.e. in May and June) (Fig. 3). Total mineral N leaching losses at the end of the respective measurement periods were 162–262 kg N ha^{-1} and 77–201 kg N ha^{-1} for Balmoral and Templeton soils, respectively (Figs. 3c, d). Oats reduced total mineral N leaching by 17% and 36% compared with that from the fallow on Balmoral soil following autumn and winter urine applications, respectively, and by 16% and 59% on Templeton soil, respectively.

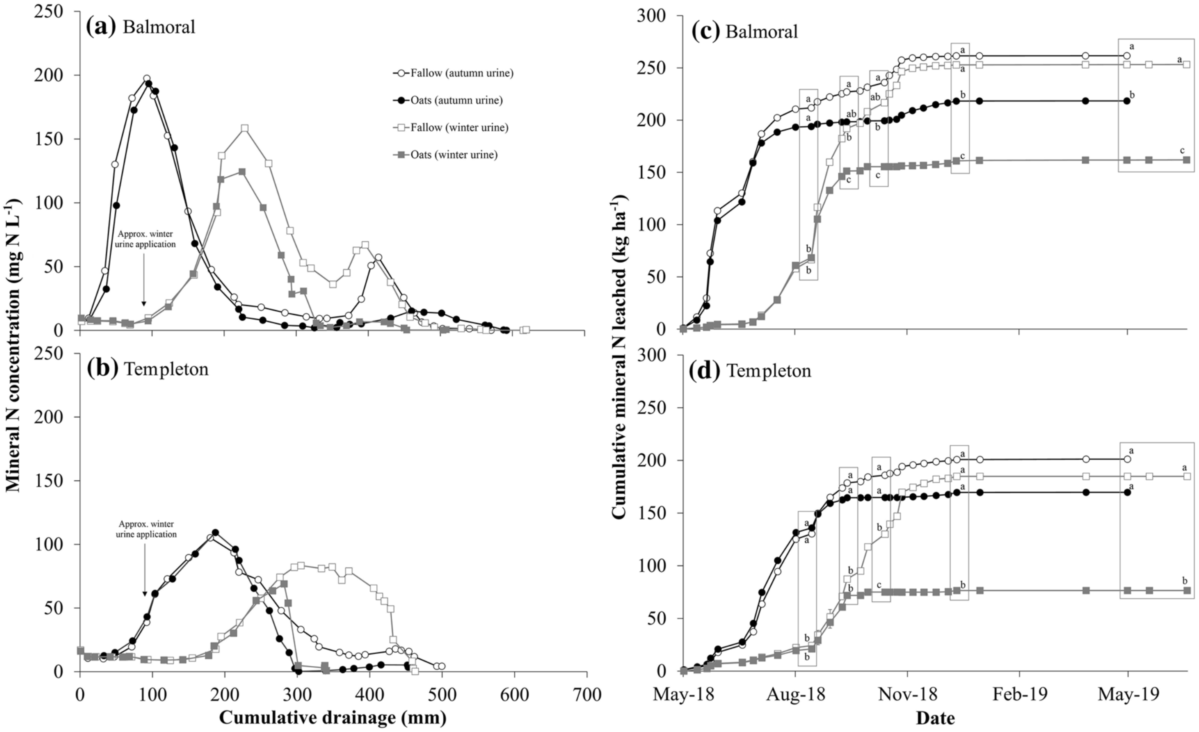

Fig. 3 Mean mineral N concentration (mg N L^{-1}) and cumulative mineral N leached (kg N ha^{-1}) in drainage water collected from monolith lysimeters after urine application (300 kg N ha^{-1}) in May or July of Experiment 2 (2018–2019) on stony Balmoral silt loam (**a** and **c**, respectively), or Templeton silt loam (**b** and **d**, respectively). Different lower case letters on a given date (within boxes) indicate significant difference, according to the LSD/LSR (least significant difference/ratio; 5%)

Table 1 Main effect means of cumulative drainage (mm) for crop/urine and soil type following artificial urine application (300 kg N ha^{-1}) in 2017 (Experiment 1), Lincoln, New Zealand

Variable	Cumulative drainage (mm)			
	26-Sept	12-Oct	27-Oct	8-Dec
Main effect means				
Soil type				
Balmoral	205.9	215.5	249.0	271.7
Templeton	201.5	204.0	233.8	251.0
P value	*0.624*	*0.234*	*0.182*	*0.100*
LSD (5%)	*18.4*	*19.5*	*23.0*	*25.0*
Crop/urine				
Fallow (-urine)	207.3	216.4	253.3	291.7
Fallow (+urine)	206.1	215.4	252.3	289.0
July oats (+urine)	195.7	197.5	223.4	225.4
August oats (+urine)	205.6	209.5	236.7	239.2
P value	*0.777*	*0.478*	*0.207*	*<.001*
LSD (5%)	*26.0*	*27.6*	*32.5*	*35.4*

LSD represents the least significant difference at the 5% level

Total drainage from the lysimeters ranged from 347 to 619 mm (Fig. 3). Significant reductions (6–15%) in drainage volume were observed under oats compared with fallow controls from late September ($P<0.05$) through until the end of the trial period ($P<0.001$), when averaged across soil type and grazing time treatments (Table 2). Drainage volumes by the end of the trial were on average 8 and 23% lower for winter (cf. autumn; $P=0.013$) and Templeton (cf. Balmoral; $P<0.001$) treatments, respectively.

Catch crop yield and nitrogen uptake

Catch crop yield (t DM ha^{-1}) and aboveground N uptake (kg N ha^{-1}) following treatment applications in Exp.'s 1 and 2 are given in Tables 3 and 4, respectively.

Table 2 Main effect means of cumulative drainage (mm) for soil type, crop and grazing time following artificial urine application (300 kg N ha^{-1}) in autumn or winter 2018 (Experiment 2), Lincoln, New Zealand

Variable	Cumulative drainage (mm)				
	30-Aug	28 Sep	20-Oct	27-Dec	Final[a]
Main effect means					
Soil type					
Balmoral	209.2	314.9	357.7	513.2	572.3
Templeton	204.6	297.4	325.8	436.7	440.6
P value	*0.428*	*0.052*	*0.005*	*<.001*	*<.001*
LSD (5%)	*11.8*	*17.7*	*21.0*	*31.1*	*34.1*
Crop					
Fallow	207.6	315.2	369.9	505	537.9
Oats	206.3	297.1	313.7	444.9	475.0
P value	*0.831*	*0.045*	*<.001*	*<.001*	*<.001*
LSD (5%)	*11.8*	*17.7*	*21.0*	*31.1*	*34.1*
Grazing time					
Autumn	220.9	317.3	354.6	511.6	528.7
Winter	193.0	295.0	328.9	438.3	484.2
P value	*<.001*	*0.016*	*0.019*	*<.001*	*0.013*
LSD (5%)	*11.8*	*17.7*	*21.0*	*31.1*	*34.1*

[a]Final measurements were 16 May and 4 July 2019 for autumn and winter urine application treatments, respectively

LSD represents the least significant difference at the 5% level

Experiment 1 (sowing timing and soil type effects)

Crop/urine and soil type had significant ($P<0.05$) main treatment effects on catch crop DM yield and N uptake (regrowth material; Table 3). Crop/urine also had a highly significant ($P<0.001$) main treatment effect on N content. In addition, there were significant treatment interactions for both crop yield ($P=0.017$) and N uptake ($P<0.001$). By final harvest, Templeton oat treatments produced the greatest yields, at approximately 11.0 and 11.2 t DM ha^{-1} for July- and August-sown treatments, respectively, compared with 7.0 and 6.0 t DM ha^{-1} for the same sowing date treatments on Balmoral soil, respectively. Consequently, the total amount of crop N uptake was on average 68% higher for the Templeton soil treatments than for the Balmoral treatments ($P<0.001$). In addition, it was estimated that 36.0 and 11.8 kg N ha^{-1} was in the aboveground biomass for the July and August oat treatments, respectively, at the time the unintentional grazing by calves on 1 October (Table 3).

Experiment 2 (urine application timing and soil type effects)

At green-chop silage maturity in late October/November, highly significant ($P\leq 0.002$) main treatment effects of grazing time (autumn vs winter) were observed for oat DM yield, N content and N uptake (Table 4). In addition, there were highly significant ($P<0.001$) main treatment effects of soil type on DM yield and N uptake. Both DM yields and N uptakes by oats were highest in the winter urine application treatments compared with autumn urine applications for Balmoral and Templeton soil treatments. Oats sown in winter yielded 6.4 and 7.4 t ha^{-1} more DM and took up 33.5 and 52.4 kg ha^{-1} more N compared with autumn-sown oats on Balmoral and Templeton soils, respectively. In addition, oats on Templeton soil treatments yielded on average 79% more DM and took up 71% more N than on Balmoral soil treatments.

By the end of the measurement period, crop (oats vs fallow) and soil type had highly significant ($P<0.001$) main treatment effects on total DM harvested (oats + pasture), total pasture-DM harvested and total N uptake (Table 4). In addition, significant main treatment effects of grazing time were observed for total DM harvested ($P<0.001$) and total N uptake ($P<0.05$). The greatest amount of total DM harvested was in the winter oat treatment on Templeton soil (25 t DM ha^{-1}), 12 t ha^{-1} more DM than the equivalent fallow treatment. On Balmoral soil, total DM harvested was 7.5 t DM ha^{-1} (93%) higher in the winter-sown oat treatment than in the fallow control. The total amount of pasture-DM harvested was 2.52 t ha^{-1} higher (33%) in the fallow controls than the amounts in the oat treatments, when averaged across season and soil type (Table 4). Total N uptake patterns were similar to that of total DM harvested, with on average 77 kg ha^{-1} more N (34%) taken up by oat catch crop treatments (oats + pasture) than by fallow-pasture controls. Additionally, the total amount of N uptake by oat treatments was on average 10 and 74% higher for winter (cf. autumn) and Templeton (cf. Balmoral) treatments, respectively.

Table 3 Mean dry matter (DM) yield (t ha^{-1}), nitrogen (N) uptake (kg ha^{-1}) and N content (%) of either green-chop oats (sown into soil monolith lysimeters in July or August 2017; Experiment 1) or pasture (sown in October after a fallow period) following artificial urine application (300 kg N ha^{-1}), Lincoln, New Zealand

Soil type	Crop	Urine	Back-transformed DM yield (t ha^{-1})	Back-transformed N content (%)	Total N uptake (kg ha^{-1})
Balmoral	Pasture	–	1.21	1.47	24
	Pasture	+	1.45	1.60	34
	July oats	+	6.98	1.38	75*
	August oats	+	6.01	1.50	71*
Templeton	Pasture	–	1.72	1.45	34
	Pasture	+	1.95	1.47	38
	July oats	+	11.02	1.57	134*
	August oats	+	11.16	1.55	135*
P value			*0.019*	*0.373*	*<.001*
LSD/[LSR] (5%)			*[1.16]*	*[1.19]*	*18*
Main effect means					
Soil type					
Balmoral			2.93	1.49	51
Templeton			4.50	1.51	85
P value			*<.001*	*0.723*	*<.001*
LSD/[LSR] (5%)			*[1.08]*	*[1.09]*	*9*
Crop/Urine					
Pasture (-urine)			1.44	1.46	29
Pasture (+urine)			1.68	1.54	36
July oats (+urine)			8.78	1.47	104*
August oats (+urine)			8.19	1.53	103*
P value			*<.001*	*0.78*	*<.001*
LSD/[LSR] (5%)			*[1.11]*	*[1.13]*	*13*

*Uptake in regrowth material following unplanned grazing by calves; an additional 36.0 and 11.8 kg N ha^{-1} was estimated to have been taken up and consumed for the July and August-sown catch crops, respectively

LSD represents the least significant difference at the 5% level. LSR represents the least significant ratio at the 5% level, i.e. if the value of the ratio of the larger mean to the smaller is greater than the LSR calculation, the means should be considered statistically significantly different

Discussion

Effect of catch crops on nitrogen leaching.

Catch crops reduced nitrogen leaching

Overall, sowing an oat catch crop after autumn- or winter-applied urine significantly reduced total mineral N leaching losses by up to 59% across all treatments compared with conventional fallow treatments. Our results also showed, as hypothesised, that the sooner the catch crop is established after grazing/urine deposition, the greater the reduction in N leaching. There is a general lack of information in the literature on winter-sown catch crops; however, these results are in line with recent work by Carey et al. (2016; 2018) who, in a relatively dry winter-spring, showed that oats sown in winter between 1 and 64 days after urine application reduced NO_3^- leaching by 19–49% (after lysimeters were flushed of N at the end of the experiment), on a stony Balmoral soil in a relatively dry winter, with greater reductions when oats were sown early. In our trial, we supplemented rainfall during the winter-spring months to simulate wetter than average years (Fig. 1), to thoroughly test the efficacy of catch crops by ensuring drainage-induced movement of N occurred during

Table 4 Mean dry matter (DM) yield (t ha^{-1}), nitrogen (N) content (%; oats only) and N uptake (kg ha^{-1}) of oat catch crops (sown into soil monolith lysimeters in May or July 2018; Experiment 2) and perennial pasture (sown in October after a fallow period) harvested in November after artificial urine application (300 kg N ha^{-1}) in May or July

Soil type	Grazing time/urine application	Crop	Oats phase			Pasture phase		Oats + pasture phase	
			DM yield (t ha^{-1})	N content (%)	N uptake (kg ha^{-1})	Total pasture-DM harvested (t ha^{-1})	Total pasture-N uptake (kg ha^{-1})	Total DM harvested (t ha^{-1})	Total N uptake (kg ha^{-1})
Balmoral	Autumn	Fallow	–	–	–	7.65	168	7.65	168
		Oats	4.09	1.27	52	6.36	161	10.43	213
	Winter	Fallow	–	–	–	8.04	168	8.04	168
		Oats	10.45	0.81	85	5.5	270	15.49	355
Templeton	Autumn	Fallow	–	–	–	11.81	278	11.81	278
		Oats	9.30	0.98	91	9.69	271	18.97	362
	Winter	Fallow	–	–	–	13.47	217	13.47	217
		Oats	16.72	0.85	143	9.34	255	25.15	398
P value			*0.419*	*0.024*	*0.352*	*0.462*	*0.395*	*0.035*	*0.795*
LSD/[LSR] (5%)			*2.01*	*0.20*	*31*	*1.085*	*76*	*[1.09]*	*41*
Main effect means									
Crop									
Fallow			–	–	–	10.24	208	9.93	229
Oats			–	–	–	7.72	239	16.66	306
P value			–	–	–	*<.001*	*0.098*	*<.001*	*<.001*
LSD/[LSR] (5%)			–	–	–	*0.542*	*38*	*[1.05]*	*21*
Grazing time									
Autumn			6.69	1.12	71	8.88	220	11.55	255
Winter			13.59	0.83	114	9.09	227	14.32	280
P value			*<.001*	*<.001*	*0.002*	*0.43*	*0.67*	*<.001*	*0.021*
LSD/[LSR] (5%)			*1.422*	*0.139*	*22*	*0.542*	*38*	*[1.05]*	*21*
Soil type									
Balmoral			7.27	1.04	68	6.89	192	9.97	195
Templeton			13.01	0.92	117	11.08	255	16.59	340
P value			*<.001*	*0.085*	*<.001*	*<.001*	*0.002*	*<.001*	*<.001*
LSD/[LSR] (5%)			*1.422*	*0.139*	*22*	*0.542*	*38*	*[1.05]*	*21*

Measurement periods following autumn and winter urine applications = 4 May 2018 to 16 May 2019 and 10 July 2018 to 4 July 2019, respectively. LSD represents the least significant difference at the 5% level. LSR represents the least significant ratio at the 5% level, i.e. if the value of the ratio of the larger mean to the smaller is greater than the LSR calculation, the means should be considered statistically significantly different

the main leaching (winter-early spring) period. The results conclusively show that sowing oats in a wet winter season, after forage crop grazing, can significantly reduce N leaching losses from these systems. The practicalities of sowing crops in wet years is an obvious challenge, and depending on the degree of cultivation required, may result in significant delays in sowing. In a meta-analysis study combined with simulation modelling, Teixeira et al. (2016) showed that the relative effectiveness of autumn-sown cover/catch crops to reduce N leaching in arable crop rotations largely depended on season and inter-annual variability (e.g. amount and timing of rainfall), typically being less effective in wetter years. Further simulation work is required to better understand the seasonal variation of catch crops in the context of cool season forage crop grazing.

Responses to soil type are seasonally dependent

Soil type was shown to have mixed effects on the efficacy of catch crops to reduce N leaching losses in our study, which is largely attributed to seasonal differences (amount and timing of rainfall), but may also partly be related to the C and N stocks associated with the different paddock histories, i.e. long-term pasture (Balmoral soil) vs short-term pasture following long-term cropping (Templeton). A further plausible explanation for the seasonal differences observed is that in Exp. 1, where mineral N concentrations in leachates from Templeton soil treatments did not reach background amounts, compared with the more freely drained Balmoral. Mineral N concentrations remained high and there was insufficient time and/or drainage for the effects of the oats to become fully apparent. Consequently, this was one of the main reasons for continuing the experiment through for at least 12 months in the second experiment, to ensure sufficient time for a full N concentration breakthrough curve to develop. Our data is not too dissimilar to other work whereby soil texture effects are tested, which also shows some inconsistency in results. A meta-analysis by Thapa et al. (2018) showed that cover crops tended to be more effective at reducing N leaching losses on coarse-textured soils (–65%) than in fine-textured soils (–43%). However, Teixeira et al. (2016) predicted a relatively low impact of soil texture/water-holding capacity on the performance of cover crops, compared with other factors such as sowing date and weather. The discrepancies observed when comparing soil type effects, both in our data and in the literature, may be due to the interacting soil and climatic factors, year to year variability in amount and timing of rainfall, as well as the soil temperature effects, which are key drivers of the various soil biological processes within the N cycle.

Delaying forage crop grazing in winter can improve the efficacy of catch crops

Urine application timing in Exp. 2 also had a notable influence on the efficacy of the oats to reduce N leaching losses, with evidence of an overall lower effect of the oats following autumn urine applications than following winter applications. This is in contrast with our hypothesis. In addition, although reductions in N leaching were observed following autumn applications under oats, a large proportion of this effect was seemingly due to the spike in mineralisation that occurred in late winter/early spring, as shown in Fig. 3a, after most of the urine-N had evidently leached. There are several possible reasons why oats were less effective at reducing losses from autumn-applied urine, including: (i) a longer period of low catch crop growth/activity (e.g. N uptake) during winter; ii) higher rates of nitrification shortly after autumn urine application compared with those in winter, because of warmer soil temperatures (Fig. 1d); and iii) approximately two months of additional drainage.

Amounts of nitrogen leaching loss measured.

Peak mineral N (NO_3^--N + NH_4^+-N) concentrations measured in the + urine Balmoral soil treatments of our study were generally higher than those of previous studies that measured N losses from urine patches under similar N loading conditions on stony Balmoral soil of grazed forage cropping systems (Hill et al. 2014; Malcolm et al. 2016a), with the exception of those recorded by Carey et al. (2016) who also measured relatively high NO_3^--N concentrations (up to approx. 240 mg NO_3^--N L^{-1}). They are, however, more aligned with results from studies where urine was applied at higher rates of N, i.e. ≥ 500 kg N ha^{-1} (Hill et al. 2015; Malcolm et al. 2015). This was also largely the case for total mineral N leaching losses, where mineral N leaching losses measured in our study were closer to those of studies where urine N was applied at higher loads. These differences might be related to the source of N, whereby the studies mentioned above used natural cow urine, while in our study we used synthetic cow urine. Although we used a recognised urine recipe to best replicate natural cow urine, it is likely that other components of natural cow urine [e.g. non-urea nitrogen compounds (Dijkstra et al. 2013; Kool et al. 2006) and carbon compounds related to diet (Peterson, M., unpublished data)] affect the N transformations in urine patch areas, and are likely to create conditions that are more conducive to immobilization, resulting in less N leaching. Recent research results reported by Yao et al. (2018) indicate that there are plant secondary metabolites (PSMs) in the urine from cows grazing on fodder beet and that these PSMs affect the soil nitrification rate.

There was a significant main treatment effect of soil type on N leaching, with losses under Templeton soil notably lower than those under Balmoral soil. This was expected, given the finer texture and higher cation exchange capacity characteristics of Templeton soil compared with Balmoral soil. For instance, work by Gaines and Gaines (1994) showed that soils of coarser texture, i.e. sand cf. silt/clay, retain less NO_3^- and result in higher leaching losses. Similarly, Di et al. (2009) reported significantly lower NO_3^- leaching losses from a very high silt content soil (93.6%) than from a sandy soil (69.1% sand, 29.0% silt), attributed to slower rates of drainage and possibly the conversion of a larger amount of NO_3^- into nitrogen gases by denitrification.

Nitrogen uptake and annual biomass production

Reductions in N leaching losses by oats were primarily driven by DM accumulation and the simultaneous uptake of N by the crop, but also through reductions in the amount of drainage volume. Soil type was a key factor in both experiments, with significantly higher amounts of N taken up in Templeton soil treatments. There was generally less drainage that occurred from Templeton soil, likely aiding the ability of oats to grow more biomass and take up more N. In Exp. 2, urine timing was another important factor affecting the amounts of N taken up, with on average 60% more N taken up by oats following winter urine applications, for the reasons described above (refer to 'Timing of application' section). In Exp. 1, the estimated amount of N consumed by calves on 1 October was 36 and 12 kg N ha^{-1} for July and August-sown oats, respectively, suggesting the total N uptake range by green-chop silage maturity for the oats might have been higher in Exp. 1 (e.g. 83–170 kg N ha^{-1}) than in Exp. 2 (Table 3). This is possible, given there was approximately 100 kg ha^{-1} more N that had leached from the fallow + urine Templeton treatment by early December in Exp. 2 than for the equivalent period of time in Exp. 1, meaning oats in Exp. 1 might have accessed more urine-N. Nevertheless, our measures of N uptake by the oats are in line with the previous lysimeter experiment of Carey et al. (2016), but are marginally lower than those obtained in a large plot field study, where uptake was recorded at 243 and 229 kg N ha^{-1} for oats sown in July and August, respectively, on Templeton silt loam (Malcolm et al. 2016b). Owing to the size of the soil monolith lysimeters, and to crops being unable to extract N from outside an area of 0.2 m^2 area, lysimeter trials of this nature may under-estimate the amount of growth and urine N that would typically be taken up by crops in an unrestricted environment (Buckthought et al. 2016), and thereby overestimate N leaching losses (because of little lateral spread potential).

With the exception of the particularly high yield after winter-applied urine on Templeton soil in Exp. 2, yields were largely within the ranges of previous similar studies (Carey et al. 2016; Malcolm et al. 2016b; 2018), and suggest that oat catch crops can not only reduce environmental impacts, but also offer farmers additional biomass production compared with traditional systems with long fallow periods. Measures of pasture yields post-harvest of the oats and in the conventional fallow treatments in Exp. 2 show that over a 12-month period, oat catch crops more than compensated for any losses in DM production during the period after oats had been harvested and the subsequent crop was established. For instance, by the end of the trial period in Exp. 2, the total amount of feed harvested from the catch crop treatments (oats + pasture) was 10–19 and 15–25 t DM ha^{-1}, for autumn and winter urine application treatments, respectively; while for conventional fallow treatments, final cumulative pasture only yields were 8–12 and 8–13 t DM ha^{-1} for autumn and winter urine treatments, respectively. This was also shown in a large on-farm field plot study by Malcolm et al. (2020), whereby oat catch crops established into an autumn-grazed forage cropping system produced more annual biomass than a conventional forage-Italian ryegrass rotation, despite initial production losses after oats were harvested.

Conclusions

Our results show that sowing an oat catch crop directly after late autumn/winter forage crop grazing on Balmoral stony silt loam and Templeton silt loam soils can reduce N leaching losses in urine patches by 9–59%, as well as enhance overall DM production potential by up to 93% in an oat-pasture rotation compared with a conventional fallow-spring pasture rotation. This practice represents an important and viable mitigation for farmers, not only to reduce their environmental footprints, but also to potentially improve the profitability of their farming operations. The effectiveness of catch crops will depend on the season (e.g. amount and timing of rainfall events), and the practical challenges of sowing crops during a typically cold and wet period of the year. Catch crops were more effective at reducing N leaching losses when urine was applied in winter, compared with autumn-applied urine. Therefore, we suggest that if possible, delaying grazing of high-yielding forage crops (particularly those on light-textured soils) for as long as possible during the cool season will enable subsequent catch crops greater opportunity to capture N before it is leached from the system. Future work should consider the effects of cultivation method and intensity when establishing catch crops on any compromises to net catch crop efficacy as a result of potentially enhanced mineralisation of N.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Addiscott TM (1996) Fertilizers and nitrate leaching. In: Hester, R.E., Harrison, R.M. (Eds.), Agricultural Chemicals and the Environment. Issues in Environmental Science Technology, R Soc Chem, pp 1–26

Buckthought LE, Clough TJ, Cameron KC, Di HJ, Shepherd MA (2016) Plant N uptake in the periphery of a bovine urine patch: determining the 'effective area.' N Z J Agric Res 59:122–140. https://doi.org/10.1080/00288233.2015.1134589

Cameron KC, Smith NP, McLay CDA, Fraser PM, McPherson RJ, Harrison DF, Harbottle P (1992) Lysimeters without edge flow: an improved design and sampling procedure. Soil Sci Soc Am J 56:1625–1628

Cameron KC, Di HJ, Moir J (2013) Nitrogen losses from the soil/plant system: a review. Ann Appl Bio 162:145–173. https://doi.org/10.1111/aab.12014

Carey PL, Cameron KC, Di HJ, Edwards GR, Chapman DF (2016) Sowing a winter catch crop can reduce nitrate leaching losses from winter-applied urine under simulated forage grazing: a lysimeter study. Soil Use Manag 32:329–337. https://doi.org/10.1111/sum.12276

Carey P, Cameron K, Di H, Edwards G (2017) Comparison of nitrate leaching from oats and Italian ryegrass catch crops following simulated winter forage grazing: a field lysimeter study. N Z J Agric Res 60:298–318. https://doi.org/10.1080/00288233.2017.1336103

Carey PL, Cameron KC, Di HJ, Edwards GR (2018) Does sowing an oats catch crop reduce nitrate leaching from urine deposition following simulated winter forage grazing?—a growth chamber experiment. Plant Soil 431:37–52. https://doi.org/10.1007/s11104-018-3742-2

Carrick S, Rogers G, Cameron K, Malcolm B, Payne J (2017) Testing large area lysimeter designs to measure leaching under multiple urine patches. N Z J Agric Res 60:205–215. https://doi.org/10.1080/00288233.2017.1291527

Carrick S, Palmer D, Webb T, Scott J, Lilburne L (2013) Stony soils are a major challenge for nutrient management under irrigation development. In: Currie LD, Christensen CL eds Accurate and efficient use of nutrients on farms http://

flrc.massey.ac.nz/publications.html. Occasional Report No. 26. Palmerston North, New Zealand, Fertilizer and Lime Research Centre, Massey University. 8 pp

Chakwizira E, de Ruiter JM, Maley S (2014) Growth, nitrogen partitioning and nutritive value of fodder beet crops grown under different application rates of nitrogen fertiliser. N Z J Agric Res 57:75–89. https://doi.org/10.1080/00288233.2013.869502

Clough TJ, Ledgard SF, Sprosen MS, Kear MJ (1998) Fate of ^{15}N labelled urine on four soil types. Plant Soil 199:195–203. https://doi.org/10.1080/00288233.2002.9513514

Cox JE (1978) Soils and Agriculture of Part Paparua County, New Zealand. New Zealand Soil Bureau Bulletin, 128 pp

Di HJ, Cameron KC, Shen JP, He JZ, Winefield CS (2009) A lysimeter study of nitrate leaching from grazed grassland as affected by a nitrification inhibitor, dicyandiamide, and relationships with ammonia oxidizing bacteria and archaea. Soil Use Manag 25:454–461. https://doi.org/10.1111/j.1475-2743.2009.00241.x

Dijkstra J, Oenema O, Van Groenigen J, Spek J, Van Vuuren A, Bannink A (2013) Diet effects on urine composition of cattle and N_2O emissions. Animal 7:292–302. https://doi.org/10.1017/S1751731113000578

Edwards GR, de Ruiter JM, Dalley DE, Pinxterhuis JB, Cameron KC, Bryant RH, Di HJ, Malcolm BJ, Chapman DF (2014) Urinary nitrogen concentration of cows grazing fodder beet, kale and kale-oat forage systems in winter. Proceedings of the 5th Australasian Dairy Science Symposium, 19–21 November, Hamilton, New Zealand

Francis GS, Haynes RJ, Williams PH (1995) Effects of the timing of plowing-in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching and spring wheat growth. J Agric Sci 124:1–9. https://doi.org/10.1017/S0021859600071185

Fraser PM, Curtin D, Harrison-Kirk T, Meenken ED, Beare MH, Tabley F, Gillespie RN, Francis GS (2013) Winter nitrate leaching under different tillage and winter cover crop management practices. Soil Sci Soc Am J 77:1391–1401. https://doi.org/10.2136/sssaj2012.0256

Gabriel J, Muñoz-Carpena R, Quemada M (2012) The role of cover crops in irrigated systems: water balance, nitrate leaching and soil mineral nitrogen accumulation. Agric Ecosyst Environ 155:50–61. https://doi.org/10.1016/j.agee.2012.03.021

Gaines TP, Gaines ST (1994) Soil texture effect on nitrate leaching in soil percolates. Commun Soil Sci Plant Anal 25:2561–2570. https://doi.org/10.1080/00103629409369207

Gal C, Frenzel W, Moller J (2004) Re-examination of the cadmium reduction method and optimisation of conditions for the determination of nitrate by flow injection analysis. Microchim Acta 146:155–164. https://doi.org/10.1007/s00604-004-0193-7

Hewitt AE, Balks MR, Lowe DJ (2021) The Soils of Aotearoa New Zealand. Springer

Hill AM, Di HJ, Cameron KC, Podolyan A (2014) The effect of animal trampling and DCD on ammonia oxidisers, nitrification, and nitrate leaching under simulated winter forage grazing conditions. J Soils Sediments 15:972–981. https://doi.org/10.1007/s11368-014-1001-6

Hill A, Di H, Cameron K, Podolyan A (2015) Comparison of dicyandiamide and biochar for reducing nitrate leaching under winter forage grazing in Canterbury, New Zealand. N Z J Agric Res 58:121–130. https://doi.org/10.1080/00288233.2014.983614

Kool DM, Hoffland E, Abrahamse SP, Van Groenigen JW (2006) What artificial urine composition is adequate for simulating soil N_2O fluxes and mineral N dynamics? Soil Biol Biochem 38:1757–1763. https://doi.org/10.1016/j.soilbio.2005.11.030

Kuzyakov Y, Domanski G (2000) Carbon input by plants into the soil. Rev J Plant Nutr 163:421–431. https://doi.org/10.1002/1522-2624(200008)163:4%3C421::AID-JPLN421%3E3.0.CO;2-R

Landcare Research (2016) Smap online [website]. http://smap.landcareresearch.co.nz/home

Malcolm BJ, Cameron KC, Edwards GR, Di HJ (2015) Nitrogen leaching losses from lysimeters containing winter kale: the effects of urinary N rate and DCD application. N Z J Agric Res 58:13–25. https://doi.org/10.1080/00288233.2014.961644

Malcolm B, Cameron K, Edwards G, Di H, de Ruiter J, Dalley D (2016a) Nitrate leaching losses from lysimeters simulating winter grazing of fodder beet by dairy cows. N Z J Agric Res 59:194–203. https://doi.org/10.1080/00288233.2016.1150307

Malcolm B, Teixeira E, Johnstone P, Maley S, de Ruiter J, Chakwizira E (2016b) Catch crops after winter grazing for production and environmental benefits. Agron N Z 46:99–108

Malcolm B, Teixeira E, Johnstone P, Maley S, de Ruiter J, Chakwizira E (2017) Establishment methods of oat catch crops after winter forage grazing. Agron N Z 47:65–77

Malcolm B, Carey P, Teixeira E, Johnstone P, Maley S, de Ruiter J (2018) Potential of catch crops to reduce nitrogen leaching in New Zealand winter grazing systems. J N Z Grassl 80:207–214. https://doi.org/10.33584/jnzg.2018.80.331

Malcolm BJ, Cameron KC, Curtin D, Di HJ, Beare MH, Johnstone PR, Edwards GR (2019) Organic matter amendments to soil can reduce nitrate leaching losses from livestock urine under simulated fodder beet grazing. Agric Ecosyst Environ 272:10–18. https://doi.org/10.1016/j.agee.2018.11.003

Malcolm BJ, de Ruiter JM, Dalley DE, Carrick S, Waugh D, Arnold NP, Dellow SJ, Beare MH, Johnstone PR, Wohler M, Brown H, Welten B, Horrocks AJ (2020) Catch crops and feeding strategy can reduce the risk of nitrogen leaching in late lactation fodder beet systems. N Z J Agric Res 63:44–64. https://doi.org/10.1080/00288233.2019.1704422

Malcolm B, Maley S, Teixeira E, Johnstone P, De Ruiter J, Brown H, Armstrong S, Dellow S, George M (2021) Performance of winter-sown cereal catch crops after simulated forage crop grazing in Southland. N Z Plants 10:108. https://doi.org/10.3390/plants10010108

Malcolm BJ (2013) The effect of pasture species composition and a nitrification inhibitor on nitrate leaching losses. PhD Thesis, Lincoln University, Canterbury, New Zealand

Matthew C, Nelson NJ, Ferguson D, Xie Y (2011) Fodder beet revisited. Agron N Z 41:39–48
Meisinger JJ, Ricigliano KA (2017) Nitrate leaching from winter cereal cover crops using undisturbed soil-column lysimeters. J Environ Qual 46:576–584. https://doi.org/10.2134/jeq2016.09.0372
Ravera BR, Bryant RH, Cameron KC, Edwards GR, Smith N (2015) Use of a urine meter to detect variation in urination behaviour of dairy cows on winter crops. N Z Soc Anim Prod 75:84–88
Rees R, Bingham I, Baddeley J, Watson C (2005) The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. Geoderma 128:130–154. https://doi.org/10.1016/j.geoderma.2004.12.020
Selbie DR, Buckthought LE, Shepherd MA (2015) The challenge of the urine patch for managing nitrogen in grazed pasture systems. Adv Agron 129:229–292. https://doi.org/10.1016/bs.agron.2014.09.004
Soil Survey Staff (2014) Keys to soil taxonomy, 12th edn. United States Department of Agriculture-Natural Resources Conservtion Service, Washington, DC
Teixeira E, Johnstone P, Chakwizira E, de Ruiter J, Malcolm B, Shaw N, Zyskowski R, Khaembah E, Sharp J, Meenken E, Fraser P, Thomas S, Brown H, Curtin D (2016) Sources of variability in the effectiveness of winter cover crops for mitigating N leaching. Agric Ecosyst Environ 220:226–235. https://doi.org/10.1016/j.agee.2016.01.019
Thapa R, Mirsky SB, Tully KL (2018) Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. J Environ Qual 47:1400–1411. https://doi.org/10.2134/jeq2018.03.0107
Thomas SM, Fraser PM, Hu W, Clough TJ, van der Klei G, Wilson S, Tregurtha R, Baird D (2019) Tillage, compaction and wetting effects on NO_3, N_2O and N_2 losses. Soil Res 57:670–688. https://doi.org/10.1071/SR18261
Walmsley DC, Siemens J, Kindler R, Kaiser K, Saunders M, Fichtner A, Kaupenjohann M, Osborne BA (2018) Reduced nitrate leaching from an Irish cropland soil under non-inversion tillage with cover cropping greatly outweighs increased dissolved organic nitrogen leaching. Agric Ecosyst Environ 265:340–349. https://doi.org/10.1016/j.agee.2018.06.031
WHO (2007) Nitrate and nitrite in drinking-water: background document for development of WHO guidelines for drinking-water quality. World Health Organisation Press, Geneva
Wild A, Cameron KC (1980) Soil nitrogen and nitrate leaching. In: Tinker PB (ed) Soils and agriculture. Blackwell Scientific Publications, Oxford, UK, pp 35–70
Yao B, Di HJ, Cameron KC, Podolyan A, Shen J, He J (2018) Understanding the mechanisms for the lower nitrous oxide emissions from fodder beet urine compared with kale urine from dairy cows. J Soils Sediment 18:85–93. https://doi.org/10.1007/s11368-017-1780-7