Nitrate leaching from high production forage crop sequences

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Abstract
New Zealand pastoral industries have set a goal of producing 45 t DM/ha annually from supplementary feed crops. Achieving this will require high inputs of water and nutrients that may increase the risk of nitrate leaching. This research describes nitrate leaching losses from the first year of intensively managed forage crop sequences to identify mitigation options. For cut-and-carry crops, the highest annual nitrate leaching losses were from crop sequences starting with maize compared to kale or barley. While maize-based sequences had the highest production (30-32 t DM/ha) they also had the highest N leaching losses per t DM produced (2.4 kg N/t DM). The best performing sequence was barley/oats/Italian ryegrass which produced 28 t DM/ha but leached <1 kg N/t DM produced. Based on plots treated with synthetic urine and treading, we calculated leaching losses of 70-124 kg N/ha from autumn grazed crops (forage rape or oats). In general, nitrate leaching losses were not closely linked to estimates of cumulative drainage or fertiliser N inputs but were strongly influenced by crop type, sowing date and additions of livestock urine.
Keywords: nitrogen, fertiliser, forage crops, livestock urine

Introduction
Meeting the productivity targets of the South Island dairy industry requires the production of supplementary feed crops to meet the growing demand of cows, particularly during winter. To this end, the New Zealand pastoral industries have set a goal of producing 45 t DM/ha/yr from supplementary feed crops. The industry has also set a target of reducing N leaching losses by 50% relative to baseline levels. Maximising the annual supplementary feed production on a given paddock requires the establishment of tight-fitting crop sequences that are based on seasonally-adapted crops with a high efficiency of light capture. However, meeting industries feed production targets will also require high inputs of water and nutrients that may increase the risk of N losses. This is a concern given that elevated concentrations of nitrate (NO_3^-) have been measured in shallow ground water in the Canterbury Plains and other key agricultural regions of New Zealand (Francis *et al.* 1999). The objective of this research was to quantify nitrate leaching losses from intensively managed high input, high production forage crops sequences using the Forage Crop Sequences Trial at Lincoln. This paper describes the results from the first year of this trial as the first step in identifying management practices that may help to mitigate N losses from high production forage crop systems.

Methods
Trial design and establishment
The Forage Crop Sequence Trial was established to investigate the potential to achieve 45 t DM/ha of annual supplementary feed production from carefully managed high input forage crops grown in tight-fitting rotations. The trial was established on a Paparua silt loam soil (sand at 30-50 cm) at Lincoln, New Zealand (Lat. 43°64'S; Long. 172°45'E). It comprised successive summer and winter crops grown in rotation over 2 years from 6 Oct 2007 to 5 Oct 2009. This paper reports results from the first year of the trial where a total of 6 crop sequences were compared (Table 1). The first crop in each sequence was either maize (*Zea mays* hybrid 'P39G12', Treatments 1-2), kale (*Brassica oleracea* cv 'Gruner', Treatments 3-4), or barley (*Hordeum vulgare* cv 'Salute', Treatments 5-6), each established in spring 2007. Following harvest of

Table 1 Crop sequences established in year one of the Forage Crop Sequence Trial.

Treatment		----- Crop Sequences -----	
No	ID	1st Crop	2nd Crop
1	Mw	Maize[1]	Wheat[4] (green chop)
2	Mtb	Maize[1]	Triticale[5] + Faba beans[6]
3	Kw	Kale[2]	Wheat[4] (green chop)
4	Ktb	Kale[2]	Triticale[5] + Faba beans[6]
5	Bro	Barely[3]	Forage rape[7] then Oats[8]
6	Boi	Barely[3]	Oats[8] then Italian[9]

Cultivars: Maize[1] ('P39G12'), Kale[2] (cv 'Grunner'), Barely[3] (cv 'Salute'), Wheat[4] (cv 'Morph'), Triticale[5] (cv 'Crackerjack'), Faba beans[6] (NZ variety), Forage rape[7] (cv 'Goliath'), Oats[8] (cv 'Milton'), Italian[9] (cv 'Feast II').

the first crops, the treatments were split to give a full six treatments in the second phase of each sequence (autumn/winter 2008). Following harvest of the second crops the treatments were split again to give a total of 12 treatments in the third (spring-autumn 2008/09) and fourth (autumn/winter 2009) phase of each sequence (details not shown here). The crops selected for each sequence were designed to maximise dry matter (DM) production. The sequences based on maize (treatments 1-2) or kale (treatments 3-4) were established primarily for use as cut-and-carry crops. The sequences based on barley (treatments 5-6) included crops suitable for grazing (rape, oats, multi-graze triticale) in addition to the barley which was grown for whole crop silage.

During the first and second phase of each sequence the plots were 46 x 20 m, each replicated 4 times. The trial was established in a split-plot design with main plots arranged in latinised blocks and with complete replication for all crop sequences. It was composed of two 300 x 50 m columns each containing a balanced compliment of first and second crop treatments. Columns were designed to accommodate a lateral irrigator with a 50 m boom. Plots were separated by 8 m wide ryegrass buffer strips. The trial area was previously in lucerne (*Medicago sativa*) that was sprayed (Glyphosate + tribenuron methyl) on 31 July 2007. The area was ploughed on 7 September 2007 then rolled and lime applied at 2.5 t/ha.

Crop management

Crops of barley (*Hordeum vulgare* cv 'Salute'), kale (*Brassica oleracea* cv 'Gruner') and maize (*Zea mays* hybrid 'P39G12') were sown on 23-25 October in the first phase (phase 1) of the crop sequences. Second (phase 2) crops of either wheat (*Sirius*, cv 'Morph') or triticale (cv 'Crackerjack') and faba beans (NZ variety) were sown (28 March-1 April 2008) into cultivated seedbeds following the maize (treatments 1-2) and kale (treatments 3-4) crops. Owing to the earlier harvest of barley, phase 2 crops of forage rape (cv 'Goliath') followed by oats (cv 'Milton', direct-drilled) were sown in treatment 5 on 1 February and 19 May 2008, respectively. In treatment 6, barley was followed by oats (cv 'Milton') and Italian ryegrass (cv 'Feast II', direct-drilled) sown on 1 February and 15 May 2008, respectively. All crops were managed with optimum rates of N and irrigation applied to produce maximum crop yields. The type and rate of fertiliser applied to each crop is given in Table 2. Irrigation was applied to maintain soil water deficits in the top 1.5 m of the soil within the non-limiting range of crops. The deficit typically ranged from 0-80 mm but did approach values as high as 140 mm on selected dates (de Ruiter *et al.* 2009). These deficits suggest that summer crops were rarely under moisture stress assuming the plant available water capacity (FC [0.30 v/v] – WP [0.08v/v]) to 1.5 m depth was 330 mm. Further information on the crop management inputs for the phase 1 and 2 crops was reported by de Ruiter *et al.* (2009).

Soil water and climate data

Neutron probe access tubes were installed in all main plots shortly after crop emergence and soil moisture was monitored at 20 cm intervals down to 1.50 m. Volumetric water deficits were calculated over the soil profile under each crop and used to adjust irrigation applications. Daily air and soil temperatures (LiCor 107 probes) and total incident radiation (LiCor 200 sensor) were recorded on site with Campbell loggers located adjacent to main crops of maize, kale and barley. Rainfall and irrigation were recorded with a 0.2 mm tipping bucket gauge located at the trial site. Detailed

Table 2 Type and rate of fertiliser applied to each of the first and second crops grown in the sequences.

Crops	Fertiliser at sowing	Side dressings (kg N/ha)	Total N applied (kg N/ha)
Summer crops			
Maize	300 kg/ha Nitrophoska	125 (Urea)	211
Kale	300 kg/ha DAP 15 kg/ha Boronate	250 (Urea)	282
Barley	150 kg/ha Cropmaster 15	2 x 50 (Urea)	123
Autumn/winter crops			
Wheat	200 kg/ha CropZeal20N	None	39
Triticale + faba beans	200 kg/ha CropZeal20N	None	39
Rape then Oats	200 kg/ha CropZeal20N 15 kg/ha Boronate	100 (Urea) 50 (Urea)	219
Oats then Italian ryegrass	200 kg/ha CropZeal20N	2 x 100 (Urea)	129

information on the climate (rainfall, temperature, radiation, Penman ET), soil water deficits and irrigation management at the site have been reported by de Ruiter *et al.* (2009).

Crop performance and soil fertility data

The DM production of all crops was measured through the season and at crop maturity before harvest. Details of the crop performance measurements are reported in de Ruiter *et al.* (2009; 2010). The results of MAF Q-test analyses (0-15 cm depth) made on 12 September (after cultivation) were pH 5.9, Ca 8, Olsen P 14, K 9, $S(SO_4)$ 5, Mg 7, and Na 7. Mineral N (2M KCl; Keeney & Nelson 1982) concentrations were determined from soil cores collected at 0-20, 20-40, 40-60, 60-90, 90-120, and 120-150 cm depths shortly before sowing (and fertiliser application) the summer and autumn/winter crops and following harvest of the autumn/winter crops.

Nitrate Leaching

Nitrate leaching was measured using soil solution samplers that were continuously monitored over the entire annual cycle of each crop sequence. Soil solution samples were collected from each of three samplers (3.5 cm d. PVC tubes equipped with porous ceramic tips) placed at depths of 0.60 and 1.50 m in each plot, whenever rainfall triggered a drainage event that exceeded 15 mm. The amount of drainage was calculated using a water balance model based on measurements of soil moisture through the soil profile, daily rainfall, irrigation and evapotranspiration (Jamieson *et al.* 1995). The concentrations of nitrate (NO_3^-) and ammonium (NH_4^+) in the solution samples were analysed on a Foss FIAstar 5000 analyser.

Urine treatment

A single application of synthetic urine plus simulated treading was applied in the rape/oats and oats/ryegrass treatments in early May 2008 following the harvest of the forage rape (Bro, treatment 5) and oat (Boi, treatment 6) crops and immediately before sowing the subsequent oat and Italian ryegrass crops, respectively. Two adjacent subplots (each 2 x 2 m) were established in each of the ex-barley plots to accommodate a urine treatment ("Urine", synthetic urine plus treading) and an untreated control ("Control", no treading, urine or fertiliser N applied). Comparisons were also made with the fertilised ("Fertilised") main plots that were not treated with urine or treading. Each subplot was equipped with soil solution samplers, located at 0.6 m and 1.5 m depths, and a neutron probe tube positioned between the two subplots. The urine treatment was imposed by first mowing the plots to a height of about 5 cm. Treading was then simulated by impacting the soil surface with a steel slide hammer device to apply approximately 220 kPa of pressure to the soil surface, representing the treading impact of an adult Friesian cow (Di *et al.* 2001). Synthetic urine (recipe following Clough *et al.* 1998) was then uniformly applied to trodden plot using a watering can at a rate of 800 kg N /ha.

Figure 1 Nitrate concentrations in the soil profile to a depth of 1.5 m following harvest of the A) first (Barley, Kale or Maize) and B) second (Oats/ryegrass, Forage rape/oats, Wheat, or Triticale/faba beans) crops in the forage crop sequences. Bars are LSD (0.05) for comparing treatment means within depth.

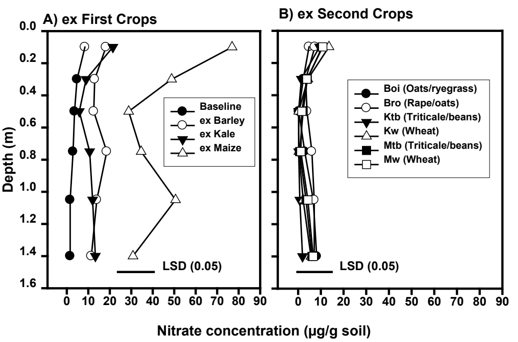

Table 3 Total fertiliser N applied, drainage and NO_3^- leached from each of the six forage crop sequences grown in year 1.

		----------- 0.6 m-----------		----------- 1.5 m-----------	
Crop Sequence	Nitrogen Fertiliser (kg N/ha)	Drainage (mm)	NO_3^- leached (kg N/ha)	Drainage (mm)	NO_3^- leached (kg N/ha)
Barley/Rape/Oats (Bro)	342	287	43	255	15
Barley/Oats/Ryegrass (Boi)	252	330	26	258	31
Kale/Wheat (Kw)	321	325	79	266	34
Kale/Triticale+bean (Ktb)	321	306	40	256	28
Maize/Wheat (Mw)	250	340	73	260	53
Maize/Triticale+bean (Mtb)	250	345	77	277	53
LSD (0.05)		52	31	57	20

Statistical Analysis

Treatment effects were analysed by ANOVA and differences between treatment means evaluated by Least Significant Differences (LSD) at the 5% level. Data were analysed using GenStat version 12.

Results and Discussion

The average total biomass production of summer crops was 23.2, 21.3 and 16.4 t DM/ha for maize, kale and barley, respectively. Other crop performance information has been reported by de Ruiter *et al.* (2009). The total crop water use by maize, kale and barley was 659, 650 and 398 mm, respectively. However, owing to differences in soil water deficits imposed by the crops over time in association with differences in crop growth rates and duration (de Ruiter *et al*. 2009), the drainage of water from the top 0.6 m of soil under maize (93 mm) and kale (72 mm) was considerably higher than that of the earlier harvested barley crop (24 mm).

Nitrate leaching losses from the summer crops at 0.6 m depth were low but significantly different ($P<0.05$), ranging from near zero losses under barley to 10 and 25 kg N/ha under kale and maize, respectively (data not shown). The NO_3^- leached under maize and kale crops at this depth was primarily associated with two drainage events where heavy rainfall followed a recent irrigation application. The difference in the NO_3^- leached from all three crops was more consistent with differences in drainage than fertiliser N inputs, though a full interpretation of these results requires a detailed N budget over time (i.e. during crop development) that is beyond the scope of this paper. Very low levels of NO_3^- leaching (0.5 to 6 kg N/ha) were also recorded under the summer crops at 1.5 m depth though these losses are most likely associated with mineral N that was in the soil profile at the time the first crops were sown.

Despite low levels of nitrate leaching from the first crops, there were differences in the concentration of NO_3^- remaining in the soil profile following their harvest that were consistent with the differences in NO_3^- leached from the first crops (Fig. 1). Nitrate concentrations following barley and kale ranged from about 20 µg N/g in the top 20 cm to about 12 µg N/g at the 1.2-1.5 m depth. On average, these concentrations were only about 10 µg N/g higher than the levels measured before the establishment of the crops in October (baseline). In contrast, nitrate concentrations following the maize crops ranged from about 75 µg N/g in the top 20 cm to as low as 30 µg N/g at 1.2-1.5 m depth. There was a significant NO_3^- bulge at the 0.9-1.2 m depth where concentrations exceeded 50 µg N/g. As

Table 4 Total dry mater production and the amount of nitrate leached per unit of dry matter produced from each of the six forage crop sequences grown in year 1.

		NO_3^- leached per unit of Dry Matter	
Crop Sequence	Total Dry Matter (t/ha)	0.6 m depth (kg N / t DM)	1.5 m depth (kg N / t DM)
Barley/Rape/Oats (Bro)	24.0	1.8	0.6
Barley/Oats/Ryegrass (Boi)	28.1	0.9	1.1
Kale/Wheat (Kw)	24.4	3.2	1.4
Kale/Triticale+bean (Ktb)	26.1	1.5	1.1
Maize/Wheat (Mw)	30.0	2.4	1.8
Maize/Triticale+bean (Mtb)	32.5	2.4	1.6

Table 5 Effects of synthetic urine amendments on the drainage and NO_3^--N leached from each of the second crops in the ex-barley forage crop sequences.

		----------- 0.6 m ------------		------------- 1.5 m ----------------	
Crop [1] Treatments	N Applied (kg/N ha)	Drainage (mm)[1]	NO_3 Leached (kg N/ha)	Drainage (mm)	NO_3 Leached (kg N/ha)
Rape/Oats (Bro)					
Control	0	220	43	190	14
Fertilised	219	263	45	217	19
Urine	800	220	134	190	21
Oats/Ryegrass (Boi)					
Control	0	238	15	200	30
Fertilised	129	251	26	202	31
Urine	800	238	368	200	59
LSD (0.05)		42	44	36	19

[1] The drainage values reported for the Control and Urine treatment plots are based a shared set of neutron probe measurements in each plot.

discussed below, this residual mineral N posed a risk to NO_3^- leaching during the establishment of the second crops (wheat and triticale/faba beans) that followed maize.

Drainage and nitrate leaching losses under the autumn/winter crops were much higher than those measured under the summer crops and the leaching losses were significantly affected by the previous summer crop (P<0.01). For this reason the results for the summer and autumn/winter crops were combined to investigate the effects of each forage crop sequence on drainage and NO_3^- leaching losses (Table 3). In general, there were no significant effects of the crop sequences on the total drainage of water over the first year of cropping but there was a significant effect of measurement depth. On average, the drainage from 0.6 m depth under these crop sequences was 322 mm compared to about 262 mm at 1.5 m depth over the annual cycle.

Nitrate leaching losses from the forage crop sequences were significantly affected by the first and second crops grown, the depth of measurement and their interaction. Over the full annual cycle, the NO_3^- leached from the maize-based sequences (Mw & Mtb) at 0.6 m depth (73-77 kg N/ha) was higher than all of the other crop sequences except where wheat followed kale (Kw) (Table 3). Overall, the barley-based sequences had the lowest total NO_3^- leaching losses from 0.6 m depth; the losses from Bro (43 kg N/ha) being slightly higher than the losses from Boi (26 kg N/ha). The relatively low leaching losses from the barley-based sequences at this depth are most likely the result of higher water and N use owing to earlier establishment and higher DM production by the forage rape/oats (Bro, 7.5 t DM/ha) and oats/ryegrass (Boi, 11.6 t DM/ha) crops. For the kale-based sequences, the leaching losses from wheat (Kw, 79 kg N/ha) were much higher than the losses from triticale+faba beans (Ktb, 40 kg N/ha). In this case the triticale+faba beans established more rapidly than the wheat but their total DM production at harvest did not differ greatly (3.1 vs 4.7 t DM/ha, respectively). The amount of NO_3^- leached from 0.6 m under these crops did not correspond with differences in total drainage or fertiliser N inputs.

Figure 2 Nitrate concentrations in the soil profile to a depth of 1.5 m following harvest of the A) Oats/Italian ryegrass and B) Forage rape/Oats grown following summer barley. The treatments include plots receiving fertiliser N, urine and unfertilised controls. Bars are LSD (0.05) for comparing treatment means within depth.

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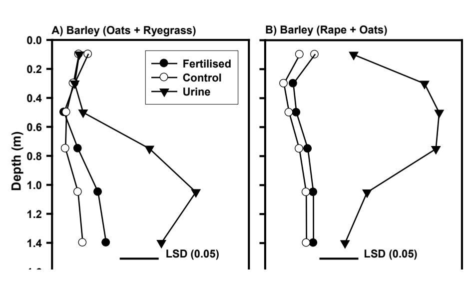

Despite similar amounts of drainage at 1.5 m depth, the average NO_3^- leached from the maize-based sequences (53 kg N/ha) were, on average, about 1.7 times those of the kale-based sequences (31 kg N/ha) and 2.3 times those of the barley-based sequences (23 kg N/ha) (Table 3). These losses are comparable to the estimated annual losses of 30-40 kg N/ha (Francis *et al.* 1999; de Klein & Ledgard 2001) from typical dairy pastures (2.5-2.8 cows/ha; 50-60 kg/ha fertiliser N) and measured annual losses of 20-75 kg N/ha in the Waikato (Ledgard *et al.* 1999) and Southland (Monaghan *et al.* 2005). Leaching losses can vary substantially from year to year in relation to winter rainfall and distributions (Francis 1995). However, this variation may be reduced, and the total NO_3^- leached increased, where irrigation is used to maintain lower soil water deficits.

The total DM production from the first and second crops grown in the forage crop sequence trial were reported previously by de Ruiter *et al.* (2009). Among the six crop sequences investigated in this study the maize-based sequences of Mw and Mtb had the highest total DM production, though these were followed closely by Bro and Ktb and the lowest DM production was recorded from the Kw and Bro sequences (Table 4). Although the maize-based (Mw & Mtb) sequences had the highest DM production, they also leached more nitrate per t DM produced (2.4 kg N/t DM) from the 0.6 m depth than all of the other crop sequences except where wheat followed kale (Kw, 3.2 kg N/t DM). Overall, the best performing sequence was Boi which produced a total of 28 t DM/ha but lost <1 kg N/t DM produced over the entire annual cycle. Although the losses from 1.5 m depth were generally lower per t DM produced, similar differences were observed between the crop sequences; with the maize-based sequences having the highest average losses and the barley-based sequences having the lowest average losses per t DM produced.

The highest nitrate leaching losses were measured at 0.6 m depth under autumn/winter crops treated with synthetic urine and simulated treading (Table 5). Nitrate leaching losses from the 0.6 m depth were nearly 2-fold higher from the urine-treated plots under ryegrass (Boi, 368 kg N/ha) than under oats (Bro, 134 kg N/ha). Leaching losses from the untreated control plots were only 5-32 % of the losses from the urine treatments and did not differ significantly from the fertilised treatments. Based on these measured losses, if we assume that approximately 30% of the soil surface area is exposed to urine when a forage crop is grazed, then the NO_3^- leached from these autumn grazed crops would be expected to range between 70 and 124 kg N/ha. Interestingly, the NO_3^- leached from 1.5 m depth was much lower than from the 0.6 m and was comparable to the losses measured at this depth under the other fertilised but ungrazed autumn/winter crops (e.g. Mw & Mtb). The NO_3^- leached from the urine-treated ryegrass plots (Boi, 59 kg N/ha) was nearly double that of the control and fertilised treatments but there were no significant effects of urine additions to the oat plots where the losses were much lower (Bro, 14-21 kg N/ha). The higher leaching loss from the urine-treated ryegrass (Boi) plots at 0.6 m was consistent with the high concentrations of NO_3^- measured in the subsoil (0.6-1.5 m) following harvest of the crop (Fig. 2). In contrast, the NO_3^- bulge recorded at 0.2-0.6 m depth in the urine-treated oat plots at crop harvest was consistent with the lower leaching loss measured from 0.6 m depth in this treatment. The high levels of residual N in the soil profile of the urine-treated plots following crop harvest may pose a risk for NO_3^- leaching during the establishment of subsequent summer crops.

Autumn/winter grazed forage crops are a potentially large source of nitrate leaching losses from intensively managed crop sequences on well drained soils of Canterbury. The differences in nitrate leaching losses measured in this study were not closely linked to cumulative drainage or fertiliser N inputs and therefore imply that crop demand for N and the timing of sowing and grazing (i.e. urine applications) are important determinants of the nitrate leaching losses. On-going work seeks to identify crops and management practices that mitigate nitrate leaching losses from high production forage crop sequences.

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