

Quantification and mitigation of nitrogen leaching in a maize silage cropping system

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Abstract

Lysimeters and suction cups were used to measure total N leaching in a high N maize crop system in the Waikato, grown in sequence with a ryegrass catch crop (RG) or left fallow in 2018/19 and 2019/20 growing seasons. This study determined appropriate depth for measuring leaching under maize (0.70 or 1.2 m depth). At least 200 kg/ha more fertiliser N than the calculated requirements was applied to the maize to ensure surplus levels. Greatest losses were observed in the fallow rotation, averaging 60 kg N/ha and 88 kg N/ha for either season, respectively, despite a drier winter. Greater leaching in 2019/20 was attributed to higher soil N concentration (+15 mg N/l) in 2020. Including RG reduced leaching by >85%, and took up at least 200 kg N/ha. Less than 10% leaching occurred during maize growing. Losses at 70 cm soil depth were almost three times higher than 120 cm. Similar amounts of isotopic ¹⁵N (1.2 %) were observed in maize grain when applied at 70 cm or 120 cm depth. Background levels, when urea was applied, was 0.37 %. Provided applied fertiliser rates match crop demand, N leaching losses from maize crops should be lower than values reported here.

Keywords: maize, ryegrass, fallow, soil depth

Introduction

Nitrogen (N) can be considered as one of the most critical nutrients for crop growth. However, if not properly managed, N leaching from cropping can significantly impact groundwater quality. In some countries, limits on crop fertiliser N inputs have been implemented (Cassman and Dobermann, 2021). The challenge with this approach is that it does not consider N fertiliser use efficiency at a farm level.

A large amount of N is required to optimise maize production and application rates should vary according to crop yield potential. For instance, a 16 t DM/ha silage crop can remove up to 200 kg N/ha compared to 250 kg N/ha for a 20 t DM/ha crop. Maize yields are impacted by weather, particularly under rainfed conditions, yet nutrient application rate decisions are generally made early in the season. Most parts of New Zealand,

including the upper and lower parts of the North Island and the upper east coast of the South Island tend to be in soil moisture deficit between December and February (NIWA, 2021), the main growing period for maize. Nitrogen leaching risk during this time is, therefore, minimal. The potential for leaching losses is greater in winter, especially if there is excess soil N. Total applied N should take into account the background soil levels. Quantification and proper management of surplus soil N after maize harvest is therefore a prerequisite to developing mitigation strategies to reduce N leaching losses in maize systems.

Unlike pasture, maize is a deep-rooted crop with an effective rooting depth of 150-180 cm in unimpeded soils (Kovacs *et al.*, 1995; Grignani *et al.*, 2007). This allows it to capture N and water from greater depths than pasture (Kristensen and Thorup-Kristensen 2004). Results from N leaching studies under maize crops in New Zealand have been variable. In a winter fallow situation, Betteridge *et al.* (2007) reported losses of 220 kg N/ha when measurements were conducted at a 60 cm depth on a pumice soil. Elsewhere, on a Papanui silt loam soil, Beare *et al.* (2010) recorded >70 kg N/ha or 53 kg N/ha when measurements were taken at a 60 cm or 150 cm soil depth, respectively, in a maize-winter cropping sequence.

Non-legume winter-active crops can be used as an effective tool to reduce N leaching during winter (Meisinger, 1991; Grignani *et al.*, 2007). Fraser *et al.* (2010) recorded leaching reductions of 76 to 119 kg N/ha when summer crops were followed by winter catch crops, relative to fallow. Similar results have been reported in other studies (FAR 2006; Malcolm *et al.*, 2016).

The objectives of the following study were to: 1) quantify the potential N leaching losses under a long-term maize plus a cut and carry winter crop system; 2) determine an appropriate depth for measuring N leaching losses under maize and 3) determine the impact of a catch crop on mitigating N leaching losses after maize silage harvest.

Materials and methods

A field experiment was carried out on an allophanic soil near Te Awamutu (37°57'07"S; 175°14'47"E; 40 m asl).

Prior to the experiment, the paddock had been in a long-term maize silage/winter annual ryegrass (RG) rotation. The research involves three independent, but related experiments, each a completely randomised block design with four replications. Rainfall and temperature data collected from the site were supplemented with long-term data from Hamilton Airport, located 16 km North East of the experimental site (Table 1).

Experiment 1

On the 27th of October 2018 and 29th of October 2019, a Pioneer maize hybrid, P1253, with a comparative relative maturity (CRM) of 109, was seeded at 110,000 plants/ha in eight four-row plots (11.5 m x 3 m), using a precision planter. Prior to planting, composite soil sampling was conducted to 15 cm depth across the experimental area to determine fertiliser requirement. Fertiliser and other management details can be found in Tsimba *et al.* (2020). In brief, all nutrients and lime applications, other than N, were based on the soil test result and paddock yield potential. Nitrogen was applied at about 400 kg N/ha to allow for surplus N after maize harvest.

Throughout the year, NO₃-N and NH₄⁺-N leaching losses were measured at 120 cm soil depth using an array of six 50 cm diameter x 120 cm high barrel lysimeters to estimate drainage, and four ceramic suction cup samplers that were spaced 2.5 m apart within each plot to measure nitrate concentration of the drained soil water. For simplicity, although leaching values reported in this study included NO₃⁻-N and NH₄⁺-N, leaching was referred to simply as N. Each suction cup sampler

was attached to a collection bottle through tubes buried 50 cm below the soil surface. The bottles were centrally located in watertight boxes and connected to a vacuum pump, which delivered a uniform vacuum across all bottles, enabling constant withdrawal of ground water whenever drainage occurred. The lysimeters drained into 5 l containers connected to their base through tubes. Once drainage was registered, the vacuum pump was triggered to initiate suction cup sampling, and the volume of water in the containers was measured using a graduated measuring cylinder.

When above ground maize biomass reached an estimated 35% dry matter content (26 March 2019 and 24 March 2020), two centre rows from each plot were harvested as silage using a two-row, small plot Wintersteiger silage chopper. Dry matter and N content were measured using a calibrated Near Infrared Spectroscopy (NIRS) system mounted on the chopper. A tetraploid annual ryegrass cultivar was then immediately direct drilled into four of the eight harvested maize plots at a rate of 30 kg/ha. No N fertiliser was added to the RG, because the purpose of experiment was to measure efficiency of RG in taking up left-over N after maize. The remaining plots were left fallow. When the RG reached about 30 cm height, two 0.5 m x 10 m strips were cut, using a push lawn mower, cutting to 5 cm height, and weighed. Two 1 kg subsamples were sent to the laboratory for N and gravimetric DM analyses.

Experiment 2

Twelve pairs of suction cups spaced 2.5 m apart were installed in four plots, consisting of fallow and RG

Table 1 Total monthly rainfalls and average monthly mean temperatures for 2018/19, 2019/20 and 1999 – 2019 seasons for Hamilton Airport.

	Monthly total rainfall (mm)			Monthly mean temperature (°C)		
	2018/19	2019/20	1999-2019	2018/19	2019/20	1999-2019
October	73	68	104	12.6	13.2	13.0
November	96	44	87	14.4	14.3	14.5
December	179	59	108	18.1	17.9	17.2
January	32	9	87	19.7	18.3	18.5
February	18	18	87	19.8	19.9	19.1
March	41	74	74	19.0	17.0	17.4
April	78	76	98	13.9	14.5	14.8
May	45	73	118	12.4	11.3	12.1
June	100	109	124	9.1	11.1	9.7
July	119	112	128	10.0	9.2	8.9
August	128	114	113	10.3	10.4	9.8
September	121	71	113	11.5	11.4	11.6
Annual	1030	828	1241	14.2	14.0	13.9

treatments. Each pair consisted of one cup installed at 70 cm depth and another one at right angles and 50 cm directly below the first. This experiment was designed to compare N leaching losses at 70 cm (standard depth generally used to measure N leaching) and 120 cm (assumed maximum effective rooting depth of maize across a range of environments). As in Experiment 1, six barrel lysimeters with 50 cm diameter and at 70 cm depth were installed to measure drainage. Leachate and drainage measurements were conducted at the same time as in Experiment 1.

Experiment 3

A maize study using ^{15}N was conducted in spring 2020 to determine the effectiveness of uptake by maize roots. The experiment consisted of three ^{15}N enriched treatments and a control. Plot area consisted of three rows, sized 2.3 m wide x 2 m long. Each row consisted of 15-16 evenly spaced maize plants sown at a density of 100,000 plants/ha. At planting, 40 kg N/ha was applied as starter fertiliser in the form of diammonium phosphate (17.6 % N). At approximately V6 maize development stage, urea (46 % N) was broadcast at a rate of 75 kg N/ha. Within a week of urea application, 30 kg N/ha in the form of liquid KNO_3 enriched with ^{15}N (5% as ^{15}N) was injected *via* a modified 8 mm diameter stainless steel pipe to a depth of 60 cm, 90 cm or 120 cm under each plant within the centre row of each treatment plot (Hodgen *et al.*, 2009). Urea at an equivalence of 30 kg N/ha was broadcast on the centre row of the control plots at the same time. Ten consecutive buffered plants within the 2 m plot were clearly marked for future sampling to trace ^{15}N uptake.

Approximately 2-4 weeks after physiological maturity (black layer) ears were removed from the treated plants for drying to constant weight in a forced

air oven. Leaves and husks were removed and stored into paper bags for air drying. The stalks were then cut at approximately 10 cm above ground level, chopped into smaller sections and split for rapid air drying in paper bags. Samples from the individual plant components (leaf, stalk and grain) were ground to 2 mm screen size in a Wiley® mill, and then to 100-mesh screen fineness with a roller mill (Arnold and Schepers, 2004) that was cleaned with ethanol between plots. Total N and isotopic N composition of plant samples were analysed at the UC Davis Stable Isotope Facility using an automated combustion elemental analyser interfaced with a continuous-flow isotope ratio mass spectrometer.

Statistical analysis

Statistical analyses were performed using Genstat version 21 (VSN International 2019). Differences in catch crop N uptake and leaching losses were subjected to analysis of variance (ANOVA). The Student-Newman-Keuls test was used to test the significance of differences between treatment means ($P \leq 0.05$).

Results

Weather, crop dry matter yields and N uptake

The average total rainfall during the 2019/20 maize growing season (October – March) was half the Waikato long term average (550 mm) and 40% less than that in 2018/19 (Table 1). The June to September rainfall totals for 2018/19 and 2019/20 were 2% and 15% lower than the Waikato long-term average, respectively.

Table 2 summarises the maize silage dry matter (DM) yields and N uptake for the maize-RG and maize-fallow (control) catch crop options. In 2019/20, maize had lower DM yields and less N uptake in plots that were fallowed the previous winter, compared to those in RG.

With RG, despite the significant DM yield differences

Table 2 Maize silage dry matter yields and nitrogen uptake for 2018/19 and 2019/20 seasons in Te Awamutu.

	Maize Silage Yield t DM/ha)		Maize N uptake (kg/ha)	
	Control	RG	Control	RG
2018/19	27.5	27.2	321.4	301.9
2019/20	23.6	25.2	141.5	207.8
Standard error of mean	0.645		20.68	
	P-value			
Season	*		*	
Catch crop	NS		NS	
Catch crop*season	NS		*	

RG, Annual ryegrass;

Catch crop refers to the winter crop treatment following maize (*i.e.*, RG or fallow);

NS, not significant;

* indicates difference significant at $P \leq 0.05$.

between the two seasons (Table 3), the difference in total N uptake between the years was not significant.

Nitrate-nitrogen leaching

Nitrate-N leaching losses were much higher in the maize-fallow than the maize-RG catch crop plots (Table 4). Whereas leaching losses in fallow plots were greater in 2019/20 than 2018/19, the opposite occurred in the RG catch crop plots.

The nitrate concentrations for the 2019/20 leachate samples from fallow plots were, on average, 15 mg N/l higher than the previous season (Figure 1). Plots with RG growing over winter had significantly lower N concentrations in both seasons.

Comparison of leaching losses measured at different soil depths

For both seasons, leaching losses were significantly greater when collected at 70 cm than 120 cm, but only in the maize-fallow rotation plots. The average N concentration was significantly greater at 70 cm than 120 cm for the fallow plots (Table 4).

Table 3 Total annual dry matter yield and total nitrogen uptake by annual ryegrass during 2018/19 and 2019/20 crop seasons in Te Awamutu.

	DM yield (t/ha)	N uptake (kg/ha)
2018/19	5.4a	215.2a
2019/20	7.4b	235.2a

Values with a different letter within a column are statistically different ($P \leq 0.05$).

Table 4 Nitrate-N leaching losses (± 1 SEM) in a maize-RG and maize-fallow rotation (control) in 2018/19 and 2019/20 crop seasons (April – October) in Te Awamutu.

	N leaching (kg/ha)	
	Control	RG
2018/19	59.6 \pm 11.65	8.8 \pm 2.96
2019/20	88.4 \pm 9.10	0.31 \pm 0.04
	P-value	
Season	NS	
Catch crop	*	
Catch crop*year	*	

RG, Annual ryegrass;

Catch crop refers to the winter crop treatment (*i.e.*, RG or control);

NS, not significant;

*, means significantly different at $P < 0.05$

Efficacy of N uptake at depth

Measurements of isotopic ^{15}N abundance in maize plant components after maturity showed evidence of N uptake from roots at 120 cm soil depth (Table 6). While the leaf component had less ^{15}N at the 90 cm and 120 cm depths than at 60 cm, there was no difference in both maize stalks and grain.

Discussion

At about 550 mm, the long-term Waikato average season rainfall during the maize growing season was just sufficient to grow a good maize crop without irrigation. If rainfall is less than crop requirement or fails to coincide with demand, supplementation from soil water residual reserves is necessary. Growing conditions in New Zealand, where evapotranspiration usually exceeds rainfall in summer, mean that leaching largely occurs in winter, when rainfall exceeds evapotranspiration rates (Di and Cameron, 2002). During the June to September period, hereafter referred to as winter, rainfall is not only important for recharging soil water reserves after summer but has the largest impact on N leaching losses. Despite the 2020 winter being much drier with less soil water drainage than 2019, N leaching in the fallow plots was greater, because N concentrations in soil water were higher than in 2019. The lower total rainfall for

Table 5 Total nitrate-N leaching losses and concentration when measured at 70 cm and 120 cm below the soil surface during the 2018/19 and 2019/20 seasons.

	Leaching losses, kg N/ha		N concentration mg/L	
	Control	RG	Control	RG
70 cm	119.2a	5.93c	51.92a	2.88c
120 cm	41.6b	2.18c	21.74b	1.49c

RG, Annual ryegrass;

Values with a different letter are statistically different ($P \leq 0.05$).

Table 6 Percentage of ^{15}N recovered in maize leaves, stalks and grain from labelled KNO_3 applied at 60 cm, 90 cm and 120 cm soil depth, compared to control during the 2019/20 season.

Depth (cm)	Leaf	Stalks	Grain
0	0.37a	0.37a	0.37a
60	0.72b	0.82b	1.07b
90	0.71bc	0.92b	1.31b
120	0.54c	0.96b	1.21b

Values with a different letter within the table are statistically different ($P \leq 0.05$).

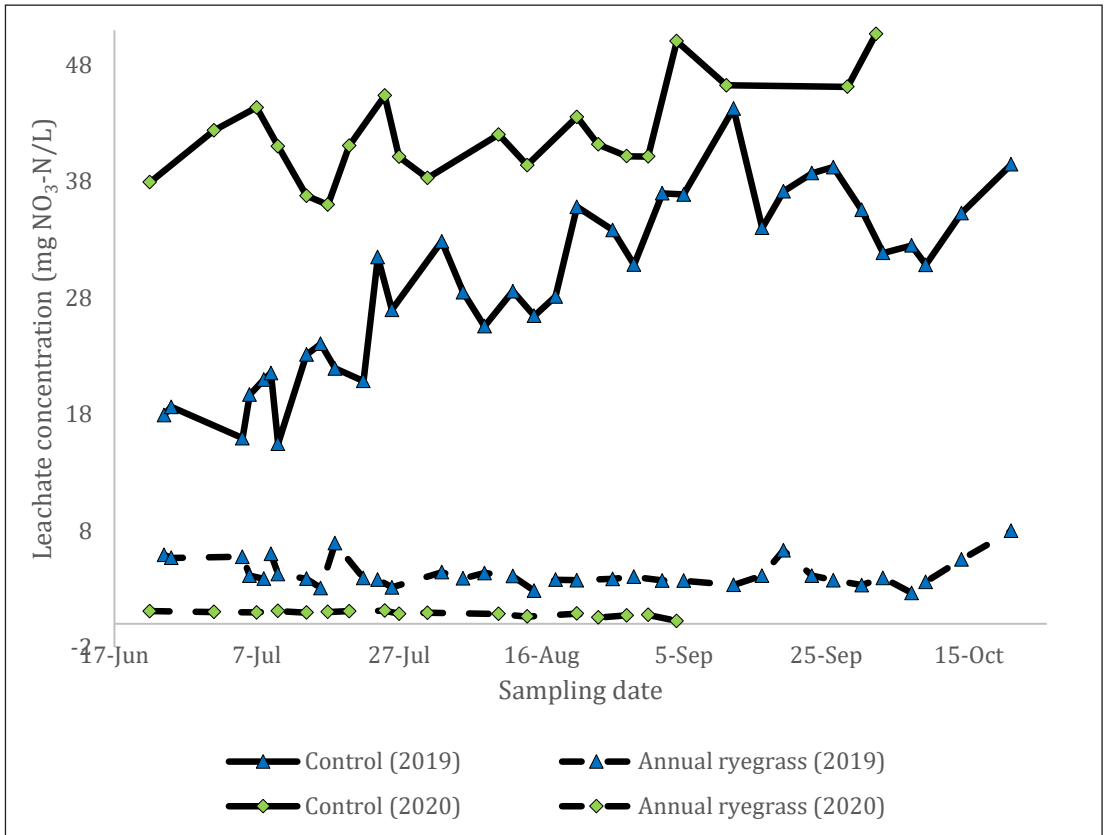


Figure 1 Nitrate-N concentrations for leachate samples collected at the 120 cm soil depth at a Te Awamutu site during the 2018/19 (2019) and 2019/20 (2020) seasons.

2019/20 reduced maize silage yield and corresponding N uptake, increasing leaching risk due to surplus soil levels. There was 160 kg more soil N/ha in the top 120 cm soil profile going into winter for 2019/20 than for the 2018/19 season (data not shown). Surplus N is one of the key indicators for determining N leaching risk (Ross *et al.*, 2008). The key to mitigating leaching appears to be the ability to capture the surplus N before it escapes beyond the rooting depth.

The importance of catch crops after maize cannot be overstated. Over the two years of this study, growing RG over winter resulted in N leaching reductions of >85%. Similar results have been reported by other workers for other crops, such as forage kale (*Brassica oleracea* L.; Carey *et al.*, 2016; 2017). Not only was RG effective at reducing N leaching, but it improved soil water storage. Gravimetric soil moisture measurements immediately after maize silage harvest showed a 7.3% greater moisture content in the top 30 cm for the annual RG than fallow plots (data not shown). This could explain the greater maize DM yields and N uptake in RG plots than seen in the previously fallowed plots for 2019/20. Soils after winter cropping tend to have improved soil

infiltration, which results in more available soil water (Frye *et al.*, 1988; Basche *et al.*, 2016).

In relative terms, the differences in DM maize yields between years was much smaller (10%) than maize N uptake (40%). This observation was consistent with 'luxury' N uptake seen in 2018/19. Luxury N uptake beyond requirement for maximum biomass production is common in maize, and acts as a buffer against potential N stresses occurring during grain-fill (Plénet and Lemaire, 2000; Ciampitti and Vyn, 2012; Nasielski *et al.*, 2019) as observed in 2019/20.

In contrast with maize, the DM yield difference in RG between the two seasons was much greater than differences in N uptake. This indicated potential luxury N uptake in 2018/19. Unlike RG, which grows vegetatively, maize is capable of remobilising the excess N towards the growing ear, reducing the total plant N relative to DM yield. Though largely influenced by growth rate, plant N content and biomass for vegetative crops are not linear, with N uptake declining as the plants get bigger and percentage N getting less over time. (Angus and Moncur, 1985; Greenwood *et al.*, 1990).

Despite high N fertiliser rates applied in this study (>200 kg N/ha above maize plant requirements), total leaching losses were much lower than the 220 kg N/ha reported by Betteridge *et al.* (2007) for pumice soil. In a simulation experiment conducted under similar conditions to the current study, Zyskowski *et al.* (2016) reported much higher leaching losses (187 kg N/ha) than those recorded in this study. This may be because measurements were at 120 cm instead of the 60 cm used by Betteridge *et al.* (2007). Less than 10% of the leaching losses were recorded during the maize growing season.

The high N fertiliser rates used in this study were to ensure surplus soil N after maize cropping in order to quantify the effectiveness of the RG catch-crop in mitigating N leaching losses. Leaching under a typical maize cropping system using the recommended amount of N fertiliser should have been much lower than the values obtained. Leaching is a function of N concentration and the volume of water that drains below a prescribed rooting depth, considered to be 120 cm in this study. Leaching measurements at shallower depths can significantly overestimate N losses. This was evident in the current research, where losses at 70 cm were three times greater than at 120 cm. Beare *et al.* (2010) reported similar findings. Maize is a deep-rooted crop, capable of extracting nutrients from a depth of up to 1.8 m (Kovacs *et al.*, 1995; FAR, 2006; Grignani *et al.*, 2007). Not all soil conditions will allow maize roots to reach such a depth, hence the choice of 120 cm was a default root depth.

On average, drainage measured at 70 cm was about 25% greater than at 120 cm. Greater leaching losses at 70 cm in fallow plots could be attributed to higher drainage. Additionally, N concentration at 70 cm was more than double compared to 120 cm, especially in fallow situations. It is clear that significant uptake of N and water occurred between 70 cm and 120 cm depth, which was consistent with Jamieson *et al.* (1995) who reported N extraction depth of about 1.5 m. Where RG was grown over winter, N concentration was significantly lower, reducing leaching risk.

Nitrogen¹⁵ isotope was traced in both maize grain and stalks, irrespective of depth of placement, which demonstrated that roots grew to 120 cm or beyond and were capable of extracting N at depth. The lower ¹⁵N concentrations in maize leaves at 120 cm could have been due to N partitioning between the ear and leaves, particularly during a dry season like 2019/20. Maize generally remobilises 45-65% of the N in grain from other plant parts (Ciampitti and Vyn, 2012; Ning *et al.*, 2017). Under stress conditions, if the plant is not capable of extracting enough soil nutrients to support grain-fill, leaves will likely be the first organs to show deficiency, which is consistent with observations of foliar N deficiency under drought (G. Edmeades, pers. comm., 2021).

Conclusions

Despite fertiliser rate having a direct influence on N leaching, actual losses can be modified by better crop management. Establishing a catch crop after maize was found to largely mitigate N leaching through increased uptake, and reduction of soil concentrations and water losses through transpiration, which impacted soil drainage volumes. Despite the high N fertiliser input for the maize crop, total N leaching losses, even in the absence of a catch crop, were not as high as has been reported in other New Zealand studies. For growers applying the appropriate amount of fertiliser, N leaching losses should be much lower than the results seen in this study.

When reporting N leaching losses in maize, it is critical that the correct depth is used, otherwise losses are likely to be overstated. The ability to trace ¹⁵N isotope applied at different depths showed maize was capable of extracting N at 120 cm depth. The evidence for the ability of catch crops to mitigate N leaching was convincing. In addition, this approach appeared to improve infiltration and moisture retention, particularly in the drier season.

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