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QUANTIFICATION OF NITROGEN LEACHING LOSSES UNDER A TYPICAL MAIZE SILAGE CROPPING SYSTEM

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Abstract

Nitrogen (N) leaching is a key contributor to current concerns with groundwater quality. When N available to the crop, from organic and inorganic sources, exceeds the amount of N required by the crop, the excess N is subject to leaching loss. Maize, an important crop for dairy and cropping farmers, has a deep rooting system which has allowed it to be used as a mitigation strategy to reduce on-farm N leaching losses in Europe.

Establishing catch crops after maize has the potential to further reduce N leaching losses. A maize-catch crop experiment utilising a series of lysimeters and suction cups was established on a long-term maize paddock in the Waikato. The goal of the study was to quantify N losses in some typical maize cropping systems. Three catch crop options (ryegrass, oats, and ryegrass-oat mix) were evaluated for their effectiveness in utilising “left-over” N after maize was harvested for silage in a cut and carry system.

About 580 kg N/ha was potentially available to the maize crop in the form of soil residual N and N fertiliser applied. This provided excess soil N after maize harvest to simulate high N input systems. On average, maize extracted 311 kg N/ha during these growing seasons whereas between 123 kg N/ha and 215 kg N/ha was removed by the catch crop over winter. The ryegrass option significantly outyielded oats by 1.8 t DM/ha. This yield difference did not necessarily translate into a difference in N leaching mitigation.

Using a series of suction cups and lysimeters, N leaching losses were measured at the 120 cm soil depth each time there was drainage at that depth. Between June and October 2019, fallow plots (control) drained 2,330 m^3/ha vs. 2,170 m^3/ha for plots with a catch crop treatment. Whereas fallow/control plots leached 64 kg N/ha below 120 cm, use of a catch crop reduced leaching to 6 kg N/ha, a 90 % reduction.

A comparison between suction cups inserted at 70 cm vs. 120 cm soil depth showed that on average, measured N leaching at 70 cm was 3.5 times higher than at 120 cm. Maize has an effective rooting depth of 1.8 m in unimpeded soils. Assuming 60 cm as the default maize rooting depth could potentially exaggerate N leaching loss measurements under maize.

Introduction

In New Zealand maize is grown on 71,700 ha, either for grain or silage, with the latter constituting 75% of the total maize area (AIMI, 2019). Maize grain is widely grown for human and animal consumption while silage is principally used as dairy supplementation. While grain area has been constant over the years, maize silage area has increased by 30% in the last three years (AIMI, 2019).

New Zealand maize silage yields have been increasing at a rate of 1.7 t DM/ha every 10 years (Morris et al., 2016). Maize is a high-yielding crop that requires a significant amount of nitrogen

(N) to optimise production. As intensification and production levels have increased over the years, so have N application levels. Nutrient requirements increase as yield levels increase. For instance, an 18 t DM/ha forage crop requires 230 kg N/ha, compared to 320 kg N/ha for a 25 t DM/ha crop.

Maize yields are significantly influenced by the weather during the growing season. Almost all production decisions (e.g. nutrient application rates and timing) need to be made early in the season when it is impossible to predict the seasonal weather. Failure to achieve the target yield, due to the negative impact of weather, could result in leftover nutrients in the soil that could leach to aquifers or enter waterways. Between 1990 and 2012 the contribution to N leaching losses from N fertilisers in New Zealand is estimated to have increased from 10 % to 18 % of the total N losses (Ministry for the Environment, 2014).

While N leaching losses from maize paddocks are not likely to be significant during the growing season, rates could be higher in winter due to greater internal drainage, particularly where the paddock is left fallow. Quantification and proper management of leftover N in the soil after maize harvest is therefore a prerequisite to developing sensible mitigation strategies against N leaching losses under a maize cropping system.

Results from N leaching studies under maize in New Zealand have been variable. In a winter fallow situation Betteridge et al. (2007) reported losses of 220 kg N/ha. Elsewhere, 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 (FAR 2005, Fowler *et al*., 2004; Grignani *et al*., 2007). A Canterbury study showed that winter crops were capable of removing 55 - 70 kg N/ha from the soil (FAR 2006).

If there are leftover nutrients after maize harvest, fertiliser applications to winter grass could be reduced, or even eliminated. To get the full benefit of winter crops, they should be mechanically harvested to minimise the environmental impact associated with grazing (McDowell & Houlbrooke, 2008.; Monaghan *et al*., 2007; Shepherd *et al*., 2008).

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 maize to capture N and water from depths 2-3 times greater than pasture (Kristensen & Thorup-Kristensen 2004). This must be taken into consideration when measuring/predicting leaching losses in maize. While nutrients below a 60 cm soil depth may be inaccessible to pasture, they are well within the reach of maize roots.

The need was identified for a study that mirrors industry best management practices for growing maize, and that included measurement of N leaching losses at a depth that reflects the effective rooting depth for maize. The objectives of this study were to: 1) quantify the potential N leaching losses below the appropriate maize rooting depth under a typical cut and carry non-grazed long-term maize cropping system and 2) compare catch crop options and their impact on winter N leaching losses after maize is harvested for silage.

Materials and methods

Field experiment set-up

The experiment was conducted on an Allophanic soil near Te Awamutu during the 2018/19 season. Rainfall and temperature data (Figure 1) were collected from a weather station situated approximately 200 m from the trial site.

Maize was planted in spring and harvested for silage in autumn. Three non-legume winter catch crop options considered to be high yielding, capable of actively growing in winter, and suitable for use as a cut and carry forage were planted after maize harvest. The experiment was designed as a completely randomised block with four replications.

On the 27th of October 2019, four rows of a Pioneer maize hybrid P1253, with a comparative relative maturity (CRM) of 109, was planted at 110,000 plants/ha in 16 plots, sized 11.5 m x 3 m, using a precision planter. The experiment area received a total of 459 kg N/ha as base, starter and side-dress fertiliser. Pre-planting soil tests indicated 123 kg/ha of potentially available N determined through anaerobic incubation. To ensure there was surplus N in the system going into winter, the total amount of N applied was higher than the crop requirement. All other nutrients were applied as per fertiliser recommendations based on soil test results.

After harvesting maize silage on the 26th of March 2019 four winter treatments were initiated. These included one fallow treatment and three catch crop treatments consisting of annual ryegrass, forage oats, and annual ryegrass - forage oat mix that were immediately direct drilled into the 16 plots. The annual ryegrass and oat options were seeded at 30 kg/ha and 100 kg/ha respectively. The mix option consisted of 20 kg/ha annual ryegrass and 50 kg/ha oats. No fertiliser was applied to the catch crops as the residual nutrient levels were considered adequate based on soil testing conducted after maize harvest.

Nitrogen leaching measurements

To measure N leaching, a series of ceramic suction cups were installed at the 120 cm soil depth to collect soil water (leachate) as it moved below the maize rooting zone. Each of the 16 plots contained four cups spaced 2.5 m apart. In a separate but related experiment, 12 pairs of suction cups were installed in four plots representing each of the catch crop treatments. These plots were situated in a separate block adjacent to the larger experiment. Each plot contained three pairs of cups (three cups at 70 cm and three at 120 cm) to compare N leaching losses at 70 cm (standard depth generally used to measure N leaching) and 120 cm.

Suction cups were arranged as an array system whereby each of the 88 cups was attached to a collection bottle via tubes buried 50 cm below the soil surface. The 88 collection bottles were located in two water-tight boxes positioned outside the experiment area. Each box contained a vacuum pump which delivered a uniform vacuum across all bottles, enabling constant drawing of leachate into collection bottles whenever there was drainage.

Depending on the intensity of drainage events, leachate sampling frequency from the collection bottles was two to three times a week. After collection, samples were immediately transferred into a chilly bin for transportation to the laboratory for mineral N analysis.

To estimate actual soil drainage, 12 lysimeters were installed to measure the total volume of water movement below the 70 cm and 120 cm soil depths. Each lysimeter consisted of an undisturbed soil column of 50 cm diameter from the experiment site. Drainage (water) was collected at the base of each lysimeter in a graduated 5 L container. The volume of drainage was measured each time leachate samples were collected from collection bottles.

Maize silage and catch crop harvest

Two centre rows of each maize plot were harvested using a Wintersteiger forage harvester. Drymatter (DM) and feed quality were estimated using near infra-red spectroscopy equipment installed on the harvester. When the catch crops reached 30 – 40 cm high, two 0.5 m x 10 m strips were cut and collected from each treatment using a lawn mower, then weighed to determine total biomass yield. Two 1 kg samples were collected for DM and mineral N analysis.

Statistical analysis

Statistical analyses were performed using Genstat version 20 (VSN International 2019). Differences in catch crop N uptake and leaching losses were analysed using analysis of variance (ANOVA). The Student-Newman-Keuls test was used to separate significant treatment means ($p \leq 0.05$). Since the comparison between 70 cm and 120 cm leachate levels were measured in a separate block, results were analysed separately.

Results

Weather

While 2018/19 mean temperatures were comparable to the 20-year average, total rainfall was less (Fig. 1). During the main growing season (11 Oct. to 26 Mar.) total rainfall was 413 mm compared to a long-term average of 486 mm. The off-season rainfall (27 Mar. to 10 Oct.) rainfall total was 627 mm which was 127 mm less than the long-term average.

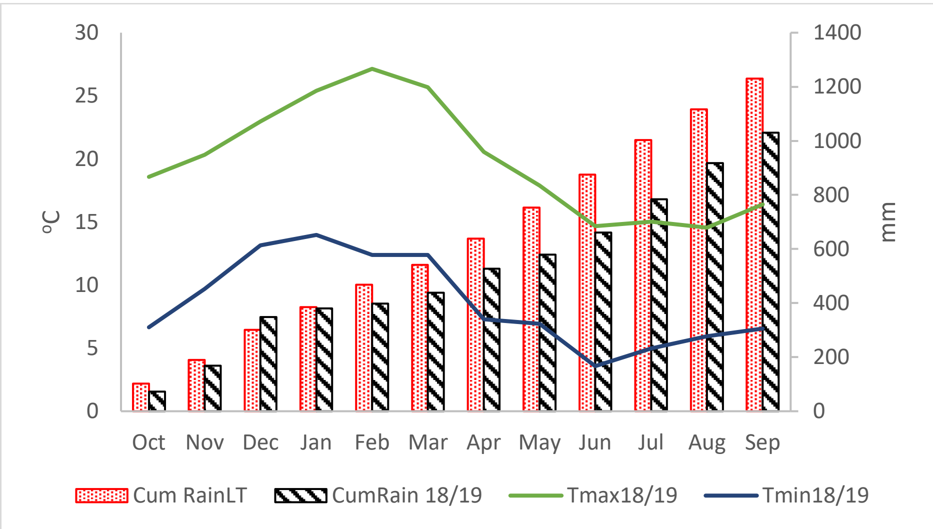

Figure 1: Average monthly temperature (October 2018 – September 2019) and 1999 – 2018 (Cum RainLT) and October 2018 – September 2019 (CumRain 18/19) cumulative rainfall for the Te Awamutu Experiment.

The amount of N leached below 120 cm after a rain event increased with rainfall ($p < 0.05$). For instance, leaching losses in fallow treatments increased by 0.075 kg N/ha/mm rainfall ($r = 0.46$). This was significantly greater than the average across the three catch crop treatments (0.007 kg N/mm rainfall; $r = 0.50$). Between June and October 2019, the total amount of drainage in the fallow and catch crop treatments was 2,330 m^3/ha vs. 2,170 m^3/ha respectively (data not shown).

Drymatter crop yields and total nitrogen uptake

Maize forage yields for the 2018-19 season averaged 27.3 t DM/ha (Table 1) with an average total N uptake of 311 kg N/ha. Among the catch crop treatments, oats had the lowest yield (3.6 t DM/ha) compared to annual ryegrass (5.4 t DM/ha) and the mixed treatment option (5.8 t

DM/ha; Table 1). The catch crop total N uptake was 124 kg N/ha, 215 kg N/ha and 208 kg N/ha for oats, ryegrass and the mixed treatment respectively.

By spring 2019, between 321 and 517 kg N/ha was accounted for as total crop uptake (Table 1). Catch crops extracted between 124 and 215 kg N/ha from the soil over winter. Assuming 270 kg N/ha was unaccounted for after maize harvest, this equates to an N recovery of up to 80 %.

Table 1: Maize and catch crop yields and nitrogen uptake (^{1}t DM/ha; ^{2}kg/ha)

Variable	Fallow	Oats	annual ryegrass	Mix
^{1}Maize	27.49a	27.78a	27.16a	26.94a
^{1}Catch crop	-	3.62a	5.44b	5.78b
^{1}Total	27.49a	31.40b	32.60b	32.72b
^{2}Total nitrogen uptake	321.4a	440.7b	517.1c	512.7c

Means within same row followed by same letter are not significantly different (P<0.05)

Nitrogen leaching measurements

The total N leaching losses measured below the 120 cm soil depth between June and October 2019 ranged from 64 kg N/ha (fallow treatment) to 3.8 kg N/ha under the mix treatment (Table 2). Relative to the 270 kg N/ha leftover after maize harvest, measured N losses below 120 cm ranged from 1 - 3 % in catch crops, compared to 24 % in fallow plots.

Table 2: Total suction cup measured N leached (kg N/ha) below a 120 cm soil depth across a range of catch crops and OverseerFM predictions between June and October 2019.

	Fallow	Oats	Annual ryegrass	Mix
Measured	64.2a	6.4b	7.4b	3.8b
OverseerFM (Long term)	59	45	52	-

Means within same row followed by same letter are not significantly different (P<0.05)

Despite OverseerFM being a long-term model that was not designed to predict annual leaching losses, for purposes of this study, a comparison between OverseerFM predictions and measured N loss data was included. The reason for doing this was to evaluate the relationship between simulated and measured readings, rather than to test the model's accuracy.

While the measured fallow plot results were comparable to OverseerFM, estimates for catch crop scenarios were significantly higher than measured values. OverseerFM does not currently simulate catch crop mixes and hence no comparison was made for those treatments.

Comparison between leaching measurements at 70 cm compared to 120 cm

The measured values for N leaching were higher at the 70 cm when compared to the 120 cm depth. The amount of N loss measured in fallow plots at 70 cm (126 kg N/ha) was almost four times the amounts measured at 120 cm (33 kg N/ha; Table 3).

Table 3: Total nitrogen leached at 70 cm compared to 120 cm soil depth

	Fallow	Oats	Annual ryegrass	Mix
70 cm measured	125.6	22.3	13.0	8.5
120 cm measured	33.3	6.5	5.6	0.4
s.e.m.	17.4	8.11	8.97	3.69
P-value	0.038	0.218	0.489	0.184

Discussion

On average, New Zealand maize silage growers with similar yield levels as reported here would supply the crop with around 350 kg N/ha (Genetic Technologies Limited, 2015). The 580 kg/ha total N available to the crop in this trial can be considered a high N leaching risk (Basso and Ritchie, 2005; Ross, et al., 2008; Long and Sun, 2012), particularly in winter.

This N level is significantly higher than recommended rates for maize and not considered a best management practice. Such rates were used to simulate a high N environment, typical of (i) maize grown after long term pasture or (ii) stress (e.g., drought) situations where applied N significantly exceeded requirements for the achieved yields.

The maize crop total N uptake was about 50 % of the plant available N (potential soil N plus applied N), leaving a significant amount of N at risk for leaching losses. Quemada et al. (2013) showed that N leaching could be reduced by 40% if fertiliser application rates matched crop demand. Greer and Pittlekow (2018) however noted that N rates that optimised yields did not necessarily minimise N leaching potential. While N fertiliser rate can have a direct influence on N leaching losses, the relationship is largely dependent on soil, management, seasonal characteristics, and crop yield (Eagle et al., 2017).

Crop N uptake will vary by soil N content which is largely influenced by factors such as fertiliser timing/placement, management, weather conditions, hybrid and harvest timing (Šidlauskas and Tarakanovas, 2004). Hence, optimising yields and minimising the environmental impact at the same time will always be a challenge. If recommended rates (350 kg N/ha) had been applied for the actual yields, almost 40 kg/ha excess N would have been applied. As Greer and Pittelkow (2018) pointed out, it is inherently difficult to minimise trade-offs between crop yield and potential N leaching losses. Incorporating a winter catch crop as part of the maize cropping programme, to utilise any excess soil N after maize harvest, will certainly be beneficial.

Despite the low N response of winter crops (DairyNZ, 2012), the 90 % reduction in leaching losses from catch crop treatments is a great example of their effectiveness as a mitigation tool against potential N loss. Similar results have also been reported in other studies (Perego et al., 2012; Carey et al., 2016; Malcolm et al., 2016; Zyskowski et al., 2016).

Even though a slight difference in plant N content among the catch crop options existed, the main determinant of total plant N uptake was yield. Greater yields meant higher N uptake (Li, et al, 2007; Huang et al., 2017) and transpiration rates (Carey et al., 2016; Malcolm et al., 2018), both lowering potential N leaching losses. A 7 % reduction in lysimeter drainage under catch crops relative to fallow treatments, indicates that N loss reduction was not only due to N uptake but also to lower drainage which can be attributed to greater transpiration losses.

Findings from this study contradict other research showing oats as higher yielding with commensurate greater N uptake than annual ryegrass (e.g., Carey, et al., 2016). This was likely because our system involved multiple cuts which better suited annual ryegrass (DairyNZ, 2011).

Conditions that promote greater total yields (e.g., timing of, and soil/weather conditions during establishment) will enhance success of N loss mitigation. In late catch crop establishment under multiple cut situations, a mix option including oats and ryegrass is likely the best choice as large seeded crops (e.g., oats) establish better under cooler conditions (Brendon Malcolm, pers. comm.). Oats will maximise N uptake initially whereas annual ryegrass yield and N uptake exceed oats significantly in later cuts.

The leaching measurements reported in this paper were for the June to October 2019 period and did not incorporate summer losses. For temperate climates with hot dry summers and wet winters (e.g., New Zealand), leaching losses largely occur in winter and early spring (Perego, et al., 2012; Svoboda, et al., 2013; Delin and Stenberg, 2014) when drainage exceeds evapotranspiration rates (Di and Cameron, 2002). In our study, consistent with the long-term average, winter rainfall constituted about 60 % of the total annual rainfall. During this same period, evapotranspiration rates are at their lowest levels. The combination of these two factors increases leaching loss risk in winter. Ongoing research (unpublished data) for the subsequent abnormally dry season only averaged 0.8 kg N/ha loss between maize planting and harvest.

Though N leaching rates increase with precipitation (Jabloun et al., 2015), the intensity of single rainfall events, distribution, and soil N concentration will have the largest impact on leaching (Daudén et al., 2004; Barton and Colmer, 2006; Perego et al., 2012; Huang et al., 2017). For instance, in our study, two periods with the greatest rainfall intensity (4^{th} to 6^{th} Jul., 59 mm and 24^{th} Sep. – 6^{th} Oct., 78 mm) constituted 21 % of the total measured leaching losses during winter. Elsewhere, Tarkalson (2006) observed a seven-fold increase in N leaching rate when annual rainfall increased from 185 to 318 mm. Huang et al. (2017) also found that N leaching increased significantly when the monthly rainfall and irrigation inputs exceeded 98.2 mm. Wang et al. (2010) hence concluded that N leaching or soil drainage can be reduced by decreasing irrigation rate and increasing irrigation frequency and/or duration.

Even though the winter period in question can be considered drier than the long-term average, it is worth noting rainfall intensity and not rainfall amount has the greatest influence on leaching (Barton and Colmer, 2006; Wang et al., 2010). In the last 20 years, the average number of rainfall events greater than 25 mm between 1 June and 25 October for the area, is three. Provided the intensity of rainfall events continues to align with historical, annual leaching losses on a similar soil are not expected to vary widely from the long-term average irrespective of total rainfall.

Despite the high starting soil N levels in our study, measured N leaching losses at 120cm were significantly lower than other local research reported (e.g., Betteridge et al., 2007). We observed an almost four-fold increase in measured N leaching losses at 70 cm compared to 120 cm. This illustrates and emphasises the importance of measuring N leaching losses at depths that accurately represent the effective crop rooting depth.

Maize is a deep-rooted crop, capable of extracting nutrients from a depth of 1.8 m (Kovacs et al., 1995; FAR, 2006; Grignani et al., 2007). Measurements at shallower depths can significantly overestimate N losses from the soil profile as observed in our research where losses at 70 cm were 3.5 times greater than 120 cm. Similar findings have also been reported by (Beare et al., 2010). Betteridge et al. (2007) reported leaching losses of 220 kg N/ha under a maize crop grown in a very high N environment where measurements were conducted at a 60 cm soil depth.

Other potential factors contributing to the lower average leaching losses, despite the high N levels applied, could be the high maize and catch crop yields, and the commensurate increased water use, which combined to reduced total soil drainage. Assuming a maize grain crop water use efficiency (WUE) of 25 kg DM/mm (Nagore, et al., 2017) a significant amount of precipitation is lost/utilised through transpiration, reducing potential soil drainage. The catch crop was also direct drilled to minimise soil mineralisation, which can be another key driver of increased soil N concentration.

The effectiveness of catch crops on mitigating N leaching is undebatable. Surprisingly, there was no direct correlation between total catch crop N uptake and N loss mitigation. Despite the significant yield and/or N uptake differences, all catch crops were equally efficient at N loss mitigation. Further investigations on correlation between initial soil N and mitigation efficiency are ongoing in a separate but related study.

Conclusion

A meaningful N leaching loss mitigation strategy should involve a maize cropping system consisting of a realistic fertilisation rate followed by a winter catch crop option. Fertiliser management should not only include an N balance calculation based on soil test results but also incorporate realistic yield goals, residual soil N, and other potential N sources to determine spring N applications. Splitting N fertilisation to align with crop use and avoiding/minimising applications in spring when leaching risk is greater will further enhance the effectiveness of the strategy.

Maize can also be used in permanent pasture regrassing situations as a mitigation strategy against N loss, provided no external N inputs are added where soil N levels are sufficient. Where maize target yields have not been achieved due to unforeseen circumstances, catch crops can be used to "mop up" the excess N and/or reduce soil drainage during winter.

Whereas this study focussed on establishing the effectiveness of catch crops in mitigating N leaching losses in a maize forage cropping system, future work will involve site-specific studies to quantify impact of soil type and conditions, N fertiliser rates/timing, and seasonal climatic conditions on N leaching.

References

AIMI (Arable Industry Marketing Initiative) 2019. New Zealand Survey of Maize Areas and Volumes: June 1, 2019. https://www.afic.co.nz/wp-content/uploads/2019/07/AIMI-MAIZE-REPORT-1-June-2019.pdf.

Basso, B. and J. T., Ritchie, 2005. Impact of compost, manure and inorganic fertilizer on nitrate leaching and yield for a 6-year maize-alfalfa rotation in Michigan. *Agr. Ecosyst. Environ.* 108, 329–341.

Barton, L., and T. D., Colmer, 2006. Irrigation and fertiliser strategies for minimizing nitrogen leaching from turfgrass. *Agr. Water Manage.* 80, 160–175.

Beare, M.H., F. Tabley, R. Gillespie, S. Maley, T. Harrison-Kirk and J. de Ruiter, 2010. Nitrate leaching from high production forage crop sequences. Proceedings of the New Zealand Grassland Association 72: 23-28.

Betteridge, K., C.J. Hoogendoorn, B.S. Thorrold, D.A. Costall, S.F. Ledgard, Z.A. Park-Ng, and P.W. Theobald. 2007. Nitrate leaching and productivity of some farming options in the Lake Taupo catchment. Proceedings of the New Zealand Grassland Association 69: 123–129.

Carey, P.L., K.C., Cameron, H.J., Di, G.R., Edwards, D.F. and Chapman. 2016. Sowing a winter catch crop can reduce nitrate leaching losses from winter-applied urine under simulated forage grazing: a lysimeter study. Soil Use and Management 32: 329-337.

DairyNZ, 2011. Information about cereal species including barley, oats, ryecorn and triticale. https://www.dairynz.co.nz/feed/crops/cereal-species/, accessed 10 April 2020.

DairyNZ, 2012. Seasonal nitrogen use. DairyNZ Farmfact 7-11. 4pp. https://www.dairynz.co.nz/media/255711/7-11_Seasonal_nitrogen_use_2012.pdf, accessed 10 April 2020.

Daudén, A., D. Quìlez, M.V. Vera. 2004. Pig slurry application and irrigation effects on nitrate leaching in Mediterranean soil lysimeters. J. Environ. Qual. 33: 2290–2295.

Delin, S. and M. Stenberg, 2014. Effect of nitrogen fertilization on nitrate leaching in relation to grain yield response on loamy sand in Sweden. *Eur. J. Agron.* 52, 291–296.

Di, H.J. and K. C., Cameron. 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosys*. 64, 237–256.

Eagle, A.J., L.P., Olander, K.L., Locklier, J.B., Heffernan and E.S. Bernhardt, 2017. Fertilizer management and environmental factors drive N2O and NO3 losses in corn: a meta-analysis. Soil. Sci. Soc. Am. J. 81, 1191–1202. doi: 10.2136/sssaj2016.09.0281

FAR, 2005. Impact of winter crop rotations on soil quality. FAR Arable Extra No. 51.

FAR, 2006. Comparing cover crops in organic farming. FAR Arable Extra No. 61.

Fowler, C.J.E., L.M., Condron, R.D., McLenaghen. 2004. Effects of green manures on nitrogen loss and availability in an organic cropping system. *New Zealand Journal of Agricultural Research 47*: 95-100.

Genetic Technologies Limited, 2015. Fertiliser application for maize. Maize Technical Insight 332. 4pp.

VSN International. 2019. Genstat *for Windows* 20th Edition. VSN International, Hemel Hempstead, UK. Web page: Genstat.co.uk.

Greer, K.D. and C.M. Pittelkow. 2018. Linking nitrogen losses with crop productivity in maize agroecosystems. Front. Sustain. Food Syst. 2:29. doi: 10.3389/fsufs.2018.00029.

Grignani, C., L., Zavattoro, D., Sacco and S. Monaco, 2007. Production, nitrogen and carbon balance of maize based forage systems. *European Journal of Agronomy 26*: 442-453.

Huang, T., X. Ju and H. Yang. 2017. Nitrate leaching in a winter wheat-summer maize rotation on a calcareous soil as affected by nitrogen and straw management. *Sci Rep* 7, 42247. https://doi.org/10.1038/srep42247.

Jabloun, M., K. Schelde, F. Tao and J. E. Olesen. 2015. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. *Eur. J. Agron.* 62, 55-64.

Kovacs, G.J., T., Nemeth and J.T. Ritchie, 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. (http://www.taki,iif.hu/cikkek/agrisys.doc). 13 pp.

Kristensen H.L., K. Thorup-Kristensen. 2004. Root growth and nitrate uptake of three different catch crops in deep soil layers, Soil Sci. Soc. Am. J. 68: 529–537.

Li, X., C., Hu, J.A. Delgado, Y. Zhang and Z. Ouyang, 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in north China plain. *Agr. Water Manage.* 89: 137-147.

Long, G. Q. and B. Sun, 2012. Nitrogen leaching under corn cultivation stabilized after four years application of pig manure to red soil in subtropical China. *Agr. Ecosyst. Environ.* 146: 73–80.

Malcolm, B.J., E.I. Teixeira, P.R. Johnstone, S.C. Maley, J.M. de Ruiter and E. Chakwizira. 2016. Catch crops after winter grazing for production and environmental benefits. Proceedings Agronomy Society of New Zealand. 46: 99-108.

Malcolm, B, P.L. Carey, E.I. Teixeira, P.R. Johnstone, S.C. Maley and J.M. de Ruiter. Potential of catch crops to reduce nitrogen leaching in New Zealand winter grazing systems. *Journal of New Zealand Grasslands 80: 207-214.*

McDowell, R.W. and D.J. Houlbrooke. 2008. Phosphorus, nitrogen and sediment losses from irrigated cropland and pasture grazed by sheep and cattle. *Proceedings of the NZ Grassland Association* 70:77-83.

Ministry for the Environment, 2014. New Zealand's greenhouse gas inventory 1990–2012. Available from www.mfe.govt.nz.

Monaghan, R. M., R.J., Wilcock, L.C., Smith, B., Tikkisetty, B.S., Thorrold, and D. Costall. 2007: Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, ecosystems and the environment* 118: 211-222.

Morris, N.J., T.D. Hurley, and R.J. Densley. 2016. National and regional maize grain and silage strip trial yields. *Journal of New Zealand Grasslands 78: 157-162.*

Nagore, M. L., A. Della Maggiora, F. H. Andrade and L. Echarte. 2017. Water use efficiency for grain yield in an old and two more recent maize hybrids. *Field Crops Res*. 214, 185–193. doi: 10.1016/j.fcr.2017.09.013

Perego, A, A, Basile, A Bonfante, R De Mascellis, F, Terribile, S, Brenna, M. Acutis. 2012. Nitrate leaching under maize cropping systems in Po Valley (Italy). *Agr. Ecosyst. Environ.* 147, 57–65.

Quemada, M., M.Baranski, , Nobel-de Lange, M. N. J., Vallejo, A. & Cooper, J. M. 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agr. Ecosyst. Environ.* 174, 1−10.

Svoboda, N. F. Taube, B. Wienforth, C. Kluß, H. Kage, A. Herrmann. 2013. Nitrogen leaching losses after biogas residue application to maize. *Soil Till. Res.* 130, 69–80.

Ross, S. M., R. C., Izaurralde, H. H., Janzen, J. A. Robertson and W. B. McGill. 2008. The nitrogen balance of three long-term agroecosystems on a boreal soil in western Canada. *Agr. Ecosyst. Environ.* 127, 241-250.

Šidlauskas, G., and P. Tarakanovas. 2004. Factors affecting nitrogen concentration in spring oilseed rape (Brassica napus L.). Plant Soil Environ., 50 (5): 227–234.

Tarkalson, D. D., J. O., Payero, S. M. Ensley, and C. A. Shapiro. 2006. Nitrate accumulation and movement under deficit irrigation in soil receiving cattle manure and commercial fertilizer. *Agr. Water Manage.* 85, 201–210.

Shepherd, M., M. Sprosen, S. Ledgard, D. Smeaton. 2009. Winter grazing of a forage crops; effects on nitrate leaching. Abstracts: 'Nutrient management in a rapidly changing world.' Fertiliser and Lime Research Centre Workshop, Massey University, February 2009.

Wang, H., X. Ju, Y. Wei, B. Li, L. Zhao, K. Hu. 2010. Simulation of bromide and nitrate leaching under heavy rainfall and high-intensity irrigation rates in North China Plain. Agr. Water Manage. 97, 1646–1654.

Zyskowski, R.F., E. Teixeira, B. Malcolm, P. Johnstone and J. de Ruiter. 2016. Effectiveness of winter cover crops to reduce nitrogen leaching losses in cropping systems in Waikato, New Zealand. Proceedings Agronomy Society of New Zealand. 46: 109-119.