A modelling approach to assessment and improvement of nitrogen management on New Zealand arable farms: a case study

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Abstract

The **S**imple **C**rop **R**esource **U**ptake **M**odel operating within the **A**gricultural **P**roduction **S**ystems s**IM**ulator (SCRUM-APSIM) was used to simulate nitrogen (N) leaching from crop rotations over 2-3 growing seasons from three arable farms in Canterbury, New Zealand. Predicted average whole-farm leaching ranged from 0.5 to 34 kg N/ha across farms and seasons. Leaching was mainly influenced by rainfall and soil type, but management practices determined the amount of soil N at risk of loss. Nitrogen leaching correlated with mineral soil N at the start of the season and/or prolonged fallow periods. The model also indicated that high residual soil N at the end of the season resulted from excessive fertiliser N application and mineralisation of N-rich crop residues. Nitrogen leaching mitigation options i.e. growing oats as a catch crop on paddocks that were fallow after summer harvest, and lower rates of fertiliser N for high soil residual N paddocks, were evaluated in SCRUM-APSIM. Growing catch crops resulted in 3-9% reduction in N leaching and an increase of New Zealand dollar ($) 6-118/ha/y in gross margins if crops were sold as animal feed. Across seasons, reducing fertiliser N to match crop requirement reduced N leaching by 2-5% and increased gross margins by $1-16/ha/y. A further evaluation of model-estimated versus farmer-estimated N fertiliser rates indicated potential to reduce fertiliser N without yield penalty. These modelling results have demonstrated the effectiveness of catch crops in reducing N leaching and highlighted the importance of using fertiliser calculators when prescribing fertiliser N rates.

Additional keywords: environment, profitability, nitrogen balance

Introduction

New Zealand regional councils are developing environmental objectives aimed at rehabilitating water systems and protecting them from further pollution, as required by the National Policy Statement for Fresh Water Management (Freshwater NPS, 2014). One of the major contributors to declining water quality is the agriculturally-derived nitrate-nitrogen (N) (Dymond *et al.*, 2013). Thus, in some catchments, environmental objectives may include imposing limits on the amount of nitrate-N leached per hectare. This calls for development of new management solutions to help farmers improve the sustainability of their farming systems.

Nitrate leaching is a naturally occurring process, and successful development of N mitigation options depends on an understanding of the factors that accelerate this process. Leaching occurs when irrigation or rainfall carries nitrate-N below the root zone. The amount of N leached depends on the soil type, crop rotation, the amount and rate of precipitation, and management practices such as tillage, stubble retention, fertiliser N rate and type (e.g. Francis *et al.,* 2006; Norris *et al.,* 2017). The greatest potential for leaching is in sandy or stony soils receiving high N fertiliser rates during periods of heavy rainfall or excessive irrigation. In New Zealand, the risk of N leaching is greatest during autumn-winter when most drainage occurs. Leached N during this period originates mainly from mineralisation of soil organic matter and residues of crops harvested in late summer (Di and Cameron 2002). Large losses of nitrate in winter can also result from mineral N remaining in the soil at harvest when excess N fertiliser is applied to spring-sown crops (Francis *et al.,* 2007). Likewise, keeping the field fallow after harvest increases leachable N in the soil due to the absence of vegetation to utilise it. Timely planting of catch crops, as demonstrated by recent studies (Malcolm *et al.,* 2016; Teixeira *et al.,* 2016), can be an effective management strategy for scavenging residual soil N. Nitrate N leaching can also be reduced by effective scheduling of irrigation, and using recommendation systems to calculate fertiliser N input and adjusting for soil mineralisation (Menneer *et al.,* 2004).

One project undertaking research to develop profitable solutions to N leaching problems in New Zealand is the Forages for Reduced Nitrate Leaching (FRNL) programme. Established in 2013, the FRNL programme has been undertaking detailed field experiments as well as whole farm simulation modelling to study management practices aimed at reducing N leaching from production systems. The modelling approach includes simulating three nominated Canterbury arable farms (monitor farms) to track the flow of N through the systems and to estimate N loss via leaching. This research includes the participation of the monitor farm owners who take part in the generation of the research questions, setting the direction of research and trialling the resulting N leaching mitigation options on their farms. This farmer-centred approach can facilitate faster adoption of management strategies that minimise N losses.

The work reported in this paper is the arable component of FRNL's 6-year project aimed at whole farm systems modelling of N flows and losses. The objectives are to monitor N leaching from nominated arable farms and to evaluate a range of mitigation strategies aimed at minimising N leaching losses from those farms.

Materials and Methods

Simulation tool

The model used in this study is the **S**imple **C**rop **R**esource **U**ptake **M**odel operating within the **A**gricultural **P**roduction **S**ystems s**IM**ulator (SCRUM-APSIM). The crop model SCRUM was developed using the mechanisms and coefficients of the OVERSEER crop model (Cichota *et al.,* 2010), and so the two models have similar functionality with regard to crop processes. However, unlike OVERSEER, SCRUM includes dynamic water and N functions to allow production to decrease in the presence of water or N stress (Khaembah *et al.*, 2015). Details of SCRUM are available at http://www.apsim.info/scrum. Within APSIM, the nutrient and soil water modules function on a daily time-scale, allowing continuous simulation of changes in the N and water status in response to weather, management and crop uptake (Holzworth *et al.*, 2014).

Monitor farms

The farms modelled in this study are located at Wakanui, Mayfield and St Andrews. The Wakanui farm (481 ha) is characterised by Wakanui silt loam, Wakanui clay loam and Templeton silt loam soil types. The Mayfield farm (522 ha) has three soil types; Templeton silt loam, Wakanui silt loam, Lismore stony silt loam and Eyre stony sandy loam soils. The St Andrews (137 ha) is part of a mixed arable-livestock block characterised by Claremont soil.

Initialisation of soil N in SCRUM-APSIM and assumptions

The Wakanui and Mayfield farms were modelled for four seasons (2013-2017), while the St Andrews farm was modelled for three seasons (2014-2017). A New Zealand season was defined as the 12 months from 1 April to 31 March. At Wakanui, soil mineral N contents determined from samples taken to a depth of 60 cm from four representative paddocks were used to estimate initial soil N levels across the farm. Soil mineral N measurements were not available for the other monitor farms and therefore, initial soil N was estimated from paddock history. In view of these estimations, the first season was considered a 'spin up' time to allow stabilisation of soil conditions in the model. Therefore, results are reported from the second season onwards.

Farmers used both quick- and slow-release N fertilisers. The slow-release function is not yet implemented in the model, and so quick release is assumed at all times.

Baseline and alternative simulations

Baseline simulations were set up using climate data from the National Institute of Water and Atmospheric Research station (NIWA, 2017) closest to the farm, S-map soil data (SMAP, 2017), and crop and management data from farm records stored on the online farm management system, ProductionWise (https://www.productionwise.co.nz) or Agworld (https://agworld.co.nz). Modelling incorporated the N returned in urine and dung at St Andrews and Mayfield to account for the grazing of crop residues and catch crops. The amounts of manure and urine returned were estimated using the procedure described by Pleasants *et al* (2007) and Shorten and Pleasants (2007). There was no grazing at Wakanui. Drainage and N leaching model outputs were estimated at the depth of 150 cm of the soil profile at Wakanui and Mayfield. At St Andrews, drainage and N leaching were based on the top 60 cm, to be consistent with the dairy part of the farm modelled by the OVERSEER model. Evaluated outputs were drainage, N leaching and residual soil N at harvest.

For Wakanui and Mayfield, alternative simulations aimed at mitigating N leaching were developed for 2014/15 and 2015/16. The mitigation options tested were (i) sowing a catch crop (oats) during the fallow period and (ii) reducing fertiliser N rates without penalising production. Increases in gross margins from lowering the fertiliser N input and sale of oats were estimated. An establishment cost of New Zealand dollar ($) 190/ha and sale price of $0.22/kg dry matter (DM) for oats were assumed.

Demonstration paddocks

As part of the monitor farm study, one or two paddocks on each farm were selected and divided into two sections to demonstrate crop performance using farmer- and model-estimated fertiliser N application rates in the 2017/18 season. Evaluated crops were barley (Wakanui and Mayfield) and Oats (St Andrews). SCRUM-APSIM fertiliser N rate calculations were based on estimated crop yield (provided by the farmer), long-term average climate data (NIWA 2017), and soil mineral N (0-90 cm) and mineralisable N (0-15 cm) measured prior to sowing. The final grain yield was estimated from plant samples from 0.25-m^2 quadrats. Demonstration paddocks were simulated again using actual yield, crop management (fertiliser N input, irrigation) and climate data, to estimate N leaching and residual N.

Results

A summary of total rainfall, fertiliser N rates, drainage and N leaching for baseline simulations is shown in Table 1.

Table 1: Model input and estimated data for three arable farms evaluated over 2-3 seasons. The model used in simulations was SCRUM-APSIM, short for the **S**imple **C**rop **R**esource **U**ptake **M**odel operating within the **A**gricultural **P**roduction **S**ystems s**IM**ulator.

Variable	Season	Wakanui	Mayfield	St Andrews
Rainfall† (mm/y)	2014/15	620	620	-
	2015/16	606	606	416
	2016/17	657	657	566
Fertiliser† (kg N/ha/y)	2014/15	248	178	-
	2015/16	183	129	166
	2016/17	167	124	130
Drainage* (mm/y)	2014/15	284	247	-
	2015/16	178	105	0.7
	2016/17	73	101	19.2
Leaching* (kg N/ha/y)	2014/15	33.7	20.2	-
	2015/16	16.2	8.5	0.5
	2016/17	10.1	8.0	6.3

† Model input values; * Model-predicted (output) values

Predicted annual N leaching at Wakanui was highest in 2014/15, and subsequently decreased over seasons. This trend was a reflection of lower predicted drainage and fertiliser N rates (Table 1). While the total annual rainfall did not follow the same trend (Table 1), the distribution was such that the farm received 325 mm of rainfall over April-July 2014, compared with 243 and 180 mm for the same period in 2015 and 2016, respectively. In all seasons, predicted N leaching from most paddocks was low (i.e. ≤20 kg N/ha/y; Fig. 1).

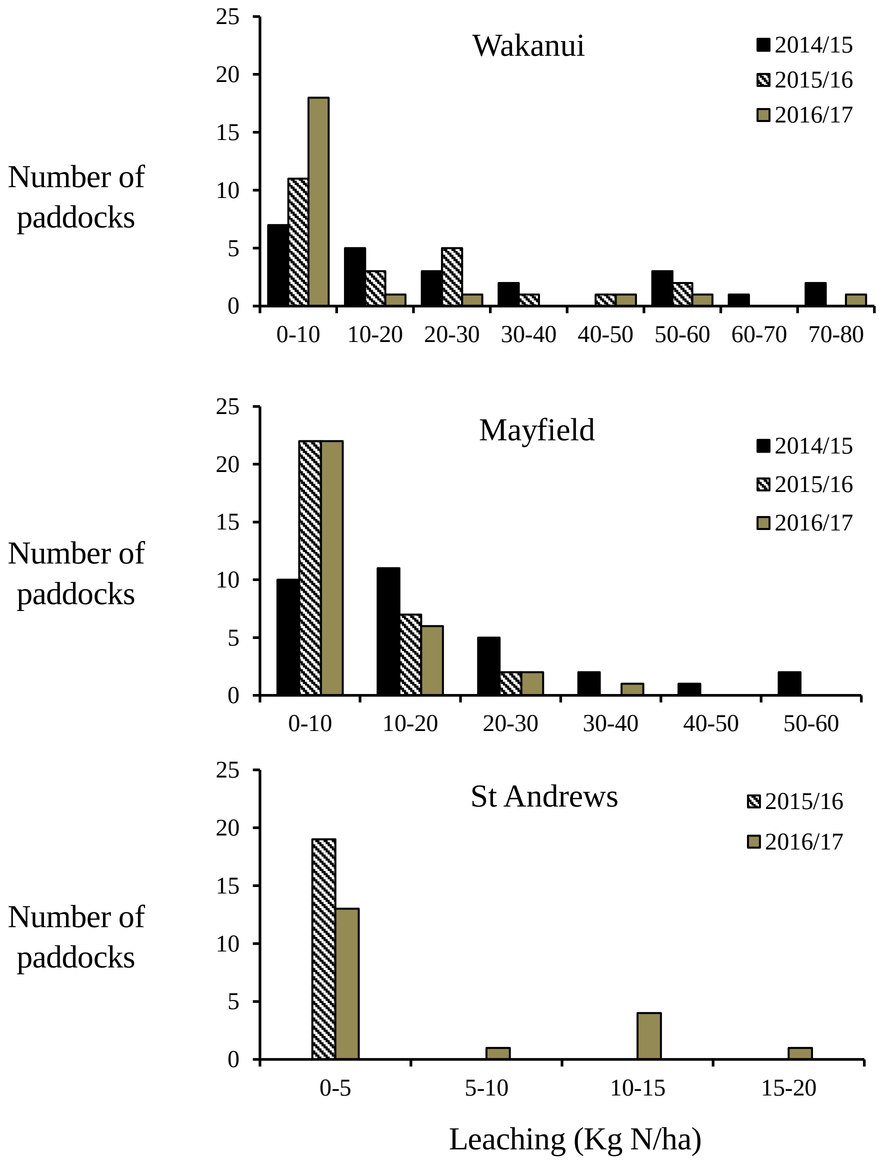

Figure 1: Frequency distribution of nitrogen (N) leaching predictions for baseline simulations from three arable farms monitored under the Forages for Reduced Nitrate Leaching (FRNL) programme.

The Wakanui farm crop rotation records showed 2-6 months of fallow following the 2014/15 summer harvest (January and March 2014) in 19 of the 23 paddocks. The number of fallow paddocks dropped to seven in 2015/16 and two in 2016/17. Model outputs indicated an association of N leaching (≥40 kg N/ha/y) with high amounts of soil mineral N originating from excessive N applied to previous crops or mineralisation of N-rich residues e.g. bean stubble (data not shown). In 2014/15, the model predicted post-summer harvest residual mineral soil N of 70-185 kg N/ha in eight paddocks. Also, in six paddocks in which wheat (a crop commonly grown on the farm) was followed by either oats (green manure) or perennial ryegrass seed crop, predicted data indicated oats were more effective at mopping up soil N.

Predicted N leaching and drainage as well as fertiliser N application rates over the seasons at Mayfield showed similar decreasing trends as seen at Wakanui (Table 1, Fig. 1). Farm records showed 11 and 12 of the 31 paddocks on the farm remained fallow after the summer harvest in 2014/15 and 2015/16, respectively. As at Wakanui, there was an association of high leaching losses with high residual soil N at harvest. For example, in 2014/15, four paddocks with residual soil N of 80-143 kg N/ha after the summer harvest, had the highest predicted N leaching values. Also, the model predicted greater drainage and leaching from paddock sections which have stony Eyre sandy loam and Lismore silt loam soils.

The St Andrews farm records showed continuous cropping over the two seasons. Model estimates indicated minimal drainage and low annual N leaching losses with most paddocks leaching 0-5 kg N/ha/y in the two modelled seasons (Table 1, Fig. 1). Climate data indicated rainfall was lower in 2015/16 than in 2016/17 (Table 1).

The alternative simulation results indicated that using oats as a catch crop reduced N leaching by 3-5% at Mayfield and 8-9% at Wakanui. The income from oats (if sold) translated into increases in gross margins of $6-25/ha/y (Mayfield) and $65-118/ha/y (Wakanui). Reducing fertiliser N to match crop N requirement reduced N leaching by 2-5% at Mayfield and 3-5% at Wakanui. Increase in gross margins from savings in fertiliser N were $1-7/ha/y for Mayfield and $7-16/ha/y for Wakanui.

The demonstration paddock information (Table 2) shows that the model estimated 20-84 kg N/ha less fertiliser N input than the farmer rates. Apart from Mayfield, paddock sections that received model-estimated N rates yielded similar or greater DM than those using farmer N rates (Table 2). Overall, model-estimated N rates resulted in greater N use efficiency (NUE; grain DM produced per kg of N applied) than farmer-estimated N input. The model predicted greater soil residual N at harvest for paddock sections using farmer N rates than those using model-estimated fertiliser N rates, except for St Andrews, which had the same amount of residual N in both sections. Modelled leaching was negligible at St Andrews, and similar between paddock sections that received farmer- and model-estimated fertiliser N rates at Mayfield (Table 2). At Wakanui, the model predicted greater leaching from paddock sections that received farmer-estimated fertiliser N input (Table 2).

Table 2: Applied nitrogen (N) fertiliser, crop yield, N use efficiency (NUE) and model-predicted N leaching residual soil N at harvest for four demonstration paddocks evaluated across three arable farms monitored under the Forages for Reduced Nitrate Leaching (FRNL) programme.

Farm – Paddock ID	Crop	N rate estimated by	*Applied N (kg N/ha)	*Yield (t DM/ha)	#NUE	†Leaching (kg N/ha)	†Residual N (kg N/ha)
Wakanui -	Barley	Farmer	205	8.99	0.88	26.0	74.0
Paddock 1		Model	140	10.39	1.34	17.2	39.0
Wakanui -	Barley	Farmer	197	9.97	0.96	33.0	29.0
Paddock 2		Model	170	13.51	1.67	29.3	19.0
Mayfield	Barley	Farmer	184	10.12	0.83	1.7	96.0
		Model	100	8.54	1.28	1.7	41.0
St Andrews	Oats	Farmer	140	9.92	1.35	-	15.0
		Model	120	10.30	1.63	-	15.0

#NUE = grain dry matter (DM) produced per kg of N applied.
* Model input parameter; † Model output parameter

Discussion

Baseline simulation results show greater N leaching in the first season and a decline over the successive 1-2 seasons modelled in this study. The dominant factor influencing this pattern was the weather, through the impact of rainfall on drainage, but management practices played a major role in determining the amount of soil N at risk of leaching, as explained below.

Management practices contributing to the reduction of N leaching over time in baseline simulations were lower average fertiliser N applied per ha on all farms and the reduction of farm area in fallow at Wakanui and Mayfield. Both these practices reduced the surplus N in the soil that was available for leaching in 2015/16 and 2016/17. There was heavy rainfall during the 2015 autumn period that caused flooding of Wakanui paddocks, making it impractical to sow crops. This contributed to the high number of fallow paddocks in 2014/15. The absence of vegetation to take up soil N at the beginning of the season (01 April 2014), coupled with the high rainfall amounts, resulted in high N leaching values on this farm. Modelled data indicated that high amounts of mineral soil N originated from excessive application of fertiliser N to spring-sown crops, and mineralisation. This shows that the use of summer-sown catch crops to mop up excessive soil N may not be guaranteed, because it is subject to weather conditions. Using recommendation systems to calculate crop fertiliser N requirements and adjusting for soil mineralisation, appears to be a more reliable approach to reducing soil N at risk of leaching during autumn-winter.

The effectiveness of catch crops in reducing N leaching during the autumn-winter demonstrated by this work supports findings by previous modelling and field experimental studies (Menneer *et al.*, 2004; Malcolm *et al.*, 2016; Teixeira *et al.*, 2016). The ability of catch crops to take up soil N depends on many factors, including type of catch crop, sowing and harvesting dates and soil tillage method (Agneessens *et al.*, 2014;

Malcolm *et al.,* 2016). In this study, modelled data indicated oats were more effective at mopping up N than perennial ryegrass at Wakanui. This was due to the oat crop establishing faster and taking up more N than perennial ryegrass. Typically, the species of the catch crop is dictated by market demand, but where farmers have a choice, selecting fast-growing, winter-active crops can result in earlier establishment of the root system and crop cover to take up water and N effectively, thus reducing N leaching. Rooting depth, although not evaluated in this study, is another important crop characteristic to be considered in selecting catch crops. For example, studies have shown that deep-rooted crops such as lucerne can effectively access deep leached nitrate-N during winter (Benoit *et al.,* 2014). The N taken up by the catch crop may be removed from the paddock (e.g. green chop) or the crop may be ploughed in and, upon decomposition, release N to be utilised by the following crop.

This study has shown that, besides excessive fertiliser N applications, mineralisation of large amounts of N-rich crop residues (e.g. beans) can contribute to high residual soil N and increase the risk of N leaching. Fast-growing catch crops sown soon after the harvest of such crops can take up some of the mineralised N and water, reducing drainage and leaching. Another way to manage N rich residues is to remove them from the field; for example, pea straw is commonly baled and used as a mulch and soil conditioner in gardens. The Wakanui and Mayfield records show burning as a way to manage crop residues, but this has sometimes been limited by fire bans.

Nitrate leaching also depends on the soil type, with greater loss associated with free draining soils and low water retention soils (Gaines and Gaines 1994; Cichota *et al.,* 2013). In this study, some of the paddock sections with the "leaky" Eyre stony sandy loam and Lismore stony silt loam leached approximately twice as much as sections with imperfectly or moderately draining Wakanui and Templeton soils. The free-draining sandy or stony soils represent "high risk factors" for N leaching and need to be managed to limit N loss. Practices most likely to minimise N losses in these soils include proper timing of fertiliser application, using efficient irrigation systems, and maintaining crop cover by prompt sowing of crops after harvest.

The St Andrews farm is characterised by heavy and poorly drained Claremont soils, which partly explains the low drainage and leaching values estimated for this farm. Because of the association of high denitrification losses with heavy clay soils (e.g. van der Salm *et al.,* 2007), the farm was assessed for the likelihood of denitrification as an alternative N loss pathway. However, predicted denitrification losses were minimal (0.1-1.8 kg N/ha /y), possibly because the low rainfall (416-566 mm/y) coupled with good management did not create conditions that were conducive to denitrification. Farm records showed prompt sowing of crops after harvest/grazing, thus allowing utilisation of residual soil N and N returned in manure and urine. It is important to note that the farm also uses under-sowing which provides continuous crop cover, but the benefits of this practice could not be estimated because this management option is not yet implemented in SCRUM-APSIM.

Farm records showing voluntary reduction of N rates over the seasons by farmers, modelled data from alternative management, and the results of the sample demonstration paddocks largely show that there is scope to reduce fertiliser N input without forfeiting yield. A decrease in fertiliser N input is good for the environment and is also a saving to the farmer because N fertiliser is one of the largest costs incurred in arable crop production. It is important to point out that the model does not differentiate between quick- and slow-release N fertilisers and so where slow-release fertiliser N was used, N leaching losses may have been over-estimated.

Conclusions

This modelling study has quantified drainage and N leaching from a sample of arable farms, in order to establish a good understanding of factors affecting N loss by leaching, and some management options to mitigate these losses. The results support earlier conclusions that rainfall is the leading factor affecting N leaching, but that farm practices determine the quantity of N at risk of loss. This study tested and demonstrated two management strategies that can reduce the amount of soil N available for leaching: calculating fertiliser N requirements with a recommendation system that accounts for soil mineralisation; and sowing catch crops immediately after the summer harvest to mop up residual soil N or N mineralised from soil organic matter and crop residues. The demonstration paddock study results indicated that there is potential for further reduction of fertiliser N input without yield penalties. However, a more comprehensive field study is required to confirm these results.

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References

Agneessens, L., De Waele, J. and De Neve, S. 2014. Review of alternative management options of vegetable crop residues to reduce nitrate leaching in intensive vegetable rotations. *Agronomy* 4: 529-555.

Benoit, M., Garnier, J., Anglade, J. and Billen, G. 2014. Nitrate leaching from organic and conventional arable crop farms in the Seine Basin (France). *Nutrient Cycling in Agroecosystems* 100: 285–299.

Cichota, R., Snow, V.O., Vogeler, I., Wheeler, D.M. and Shepherd, M.A. 2013. Describing N leaching from urine patches deposited at different times of the year with a transfer function. *Soil Research* 50: 694-707.

Cichota, R., Brown, H., Snow, V.O., Wheeler, D.M., Hedderley, D., Zyskowski, R. and Thomas, S. 2010. A nitrogen balance model for environmental accountability in cropping systems. *New Zealand Journal of Crop and Horticultural Science* 38: 189-207.

Di, H.J. and Cameron, K.C. 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems* 64: 237-256.

Dymond, J.R., Ausseil, A.G., Parfitt, R.L., Herzig, A. and McDowell, R.W. 2013. Nitrate and phosphorus leaching in New Zealand: a national perspective. *New Zealand Journal of Agricultural Research* 56: 49-59.

Francis, G.S., Thomas, S.M., Barlow, H.E., Tabley, F.J. and Gillespie, R.N. 2006. Fertiliser and irrigation management effects on nitrate leaching from rotations of annual crops. *In*: Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Francis, G.S., Thomas, S.M., Barlow, H.E., Tabley, F.J., Gillespie, R.N. and Zyskowski, R.F. 2007. Management strategies to minimise nitrate leaching from arable crops. *In*: Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Gaines, T.P. and Gaines, S.T. 1994. Soil texture effect on nitrate leaching in soil percolates. Pp 2561-2570.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C. and others. 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* 62: 327-350.

Khaembah, E.N., Brown, H.E., Sharp, J.M. and Zyskowski, R. 2015. Soil nitrogen and soil water dynamics in crop rotations: Estimation with the multiple crop single purpose model. *In*: Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Malcolm, B., Teixeira, E., Johnstone, P., Maley, S., de Ruiter, J. and Chakwizira, E. 2016. Catch crops after winter grazing for production and environmental benefits. *In*: Proceedings of Agronomy New Zealand. Pp. 99-108.

Menneer, J.C., Ledgard, S.F. and Gillingham, A.G. 2004. Land use impacts on nitrogen and phosphorus loss and management options for intervention. Report prepared for Environment Bay of Plenty.

NIWA, 2017. National Institute of Water and Atmospheric Research, http://cliflo.niwa.co.nz.

Norris, M., Johnstone, P., Green, S., van der Klei, G., van den Dijssel, C., Wright, P., Clark, G., Thomas, S., Williams, R., Mathers, D. and others. 2017. Rootzone reality - a network of fluxmeters measuring nutrient losses under cropping rotations. Summary of year 1 and year 2 results. In: Currie LD, Hedley MJ eds. Science and policy: nutrient management challenges for the next generation. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp. 10.

NPS F 2014. National Policy Statement for Freshwater Management 2014 (NPS-FM 2014), http://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2014

Pleasants, A.B., Shorten, P.R. and Wake, G. 2007. The distribution of urine deposited on a pasture from grazing animals. *Journal of Agricultural Science* 145: 81-86.

Shorten, P.R. and Pleasants, A.B. 2007. A stochastic model of urinary nitrogen and water flow in grassland soil in New Zealand. *Agriculture, Ecosystems & Environment* 120: 145-152.

SMAP, 2017. The digital soil map for New Zealand, https://smap.landcareresearch.co.nz.

Teixeira, E.I., Johnstone, P., Chakwizira, E., de Ruiter, J.M., Malcolm, B., Shaw, N., Zyskowski, R., Khaembah, E., Sharp, J., Meenken, E. and others. 2016. Sources of variability in the effectivenes of winter cover crops for mitigating N leaching. *Agriculture, Ecosystems & Environment* 220: 226-235.

van der Salm, C., Dolfing, J., Heinen, M. and Velthof, G.L. 2007. Estimation of nitrogen losses via denitrification from a heavy clay soil under grass. *Agriculture, Ecosystems & Environment* 119: 311-319.