New Knowledge Register

March 2020

Forages for Reduced Nitrate Leaching

Scientific manuscripts and published conference proceedings

Forages for Reduced Nitrate Leaching

Scientific manuscripts and published conference proceedings

Forages for Reduced Nitrate Leaching was a DairyNZ-led collaborative research programme across the primary sector delivering science for better farming and environmental outcomes, aimed at reducing nitrate leaching through research into diverse pasture species and crops for dairy, arable and sheep and beef farms. The main funder was the Ministry of Business, Innovation and Employment, with co-funding from research partners DairyNZ, AgResearch, Plant & Food Research, Lincoln University, Foundation for Arable Research and Manaaki Whenua-Landcare Research.

Contents

Introduction

The ***Forages for Reduced Nitrate Leaching*** programme (FRNL; 2013-2019) combined fundamental, strategic and applied research, co-development and extension, to achieve and demonstrate practical, adoptable options for pastoral, arable and mixed farms to reduce nitrate leaching losses while maintaining or improving productivity and profitability. The main hypotheses of the programme were that this can be achieved by

(1) reducing urinary nitrogen (N) excretion from livestock through the use of diverse pastures (i.e. mixtures containing grasses, legumes and herbs) and/or forage crops with a lower N content, without any reduction in animal performance;

(2) improving N use efficiency of pasture and crops through the use of species and crop rotations that increase the uptake of soil N and thereby reducing N fertiliser input; and

(3) a co-development approach ensuring close collaboration with end-users (farmers, rural professionals) to improve applicability and adoptability.

This document summarises key results of FRNL's six years of research and co-development. It provides easy access to research results by listing all scientific output and papers published in proceedings of scientific and industry conferences and providing links to them.

The document is structured in accordance to the programme, with three clusters of work (so-called Research Aims):

1. Alternative pasture species (led by Grant Edwards; Lincoln University)
2. Crops (led by Mike Beare, Plant & Food Research)
3. Farm systems (led by Ina Pinxterhuis, DairyNZ)

Within each Research Aim, a number of projects were executed. In this document these are grouped where they contributed to a common goal. Titles of the various sections reflect these goals. We trust this structure helps you finding the publications relevant to your interest.

Benefits of alternative species in pastures to reduce nitrate leaching from livestock systems

Nitrogen (N) excretion from livestock and N uptake by plants can be improved through the use of herbs, grass and legume pasture species other than perennial ryegrass and white clover. These alternative pasture mixtures can lead to more N being partitioned to animal product and less N excreted in urine. Additionally, herbs can reduce the N concentration of urine, which reduces the load of N (kg N/ha equivalents) in urine patches. Reduced urine N excretion and reduced N load can reduce nitrate leaching.

Pasture species that exhibit greater growth rates in the cooler seasons can help when risk of drainage is greater, and hence risk of N leaching.

This research aimed to define the critical plant species and amounts required in a mixture, and associated management, to decrease N excretion in urine and increase N uptake from soils by plants.

Diverse pastures to reduce urinary N excretion: Effect of species composition in the diet on N partitioning in livestock

Outdoor grazing studies in Canterbury and Waikato evaluated the effect of pasture species composition on milksolids production and urinary N excretion patterns, using urine sensors.

Data from the trials, combined with forage chemical compositions from grazing and N fertiliser management studies were used to inform and validate animal model predictions of milksolids production and N partitioning in dairy cows. The validated model was used to test the effects of an array of diets with different pasture components on N partitioning and was used in the DairyNZ Whole Farm Model (WFM) to translate effects to the whole farm scale.

A controlled feeding experiment in metabolism stalls was conducted with lactating dairy cows where the plantain content in the cows' diet (with perennial ryegrass and white clover) was manipulated. Partitioning of dietary N into milk, urine, faeces and live weight was measured.

KEY RESULTS OF THE WORK UNDERTAKEN

- Urinary N excretion (g/cow/day) is closely related to N intake, irrespective of pasture type. N intake is related to the N% of the pasture species, and the pasture botanical composition. Greater plantain content may simultaneously reduce legume content, which is important for N intake: legumes have a consistently high N%.
- Plantain in the diet altered the diurnal pattern of urine N excretion and reduced urinary N concentration in most experiments. e.g. urinary N concentration of cows grazing plantain was 56% lower than those grazing perennial ryegrass/white clover pastures, and 33% lower for cows grazing 50/50 pasture-plantain.
- Urine patch area was larger for plantain-containing pastures due to greater urine volume and increased urine patch spread because of more open swards in partially or fully grazed pasture.
- Urination frequency rather than urination volume is more likely to be increased when herb-containing pastures are fed. Herbs have a high water content and increase diet water intake and subsequently the number of urinations per day.
- In grazing trials, urine N concentration was lower in the late and early lactation for cows grazing plantain (2.4 and 2.2 g N/L respectively) and 50:50 standard perennial ryegrass/white clover pasture : plantain (3.6 and 3.4 g N/L respectively) than standard pasture (5.4 and 4.7 g N/L respectively). Urine volume in late lactation from cows grazing plantain (73.8 L/cow/day) and 50:50 pasture : plantain (59.1 L/cow/day) was greater than from those grazing perennial ryegrass/white clover (46.5 L/cow/day).

- Substitution of tall fescue and summer grass with either lucerne, or lucerne and plantain, resulted in small improvements in feed digestibility but did not increase feed intake in late lactation. Inclusion of lucerne reduced dry matter intake but maintained milk production while inclusion of plantain with lucerne maintained intake and increased milk production. Inclusion of plantain at 46-70% of DM intake increased total water intake by 8-21% over grass/lucerne swards but significantly decreased trough water intake. A high proportion of plantain in the diet of lactating cows induced a reduction in urinary N concentration in both mid-lactation and late-lactation. Increasing plantain intake decreased lucerne intake and subsequently N intake in summer.
- Voluntary daily dry matter intake of dairy cows in a metabolism stall trial increased with increasing proportion of plantain in the diet, however dietary N intake was similar (mean 545 g N/cow/d). Urinary N concentration was reduced in cows fed plantain at 30% or more of the diet compared with cows fed ryegrass only. The effect is described by a significant negative quadratic relationship between UN concentration and percentage of plantain in the diet. Increasing plantain in the diet reduced the partitioning of N to urine resulting in 15% less (39 g N /day) N partitioned to urine in cows fed 30% plantain compared to cows fed ryegrass only. When cows were fed diets containing 45% plantain, urine volume was 25% more (+9 L/cow/day) and urinary N excretion was 41% less (-66g/c/d) than from cows fed ryegrass only diets.
- Variations in circadian patterns for N excretion and urine N concentration between pasture species offers opportunity to tailor nitrate leaching mitigation options to individual pasture species, i.e. strategic use of off paddock infrastructure, low N feeds etc.
- Researchers need to take a cautionary approach when using daily urine creatinine excretion from spot samples to estimate urinary N excretion due to a 2-fold variation in urinary creatinine concentration over 24 hours.
- Modelling the effect of increase in urination frequency on nitrate leaching revealed limited reduction in leaching in Canterbury (6%) due to greater area covered in urine, though a greater reduction in N leaching was predicted for Waikato (20%) compared with conventional ryegrass/clover pastures.
- Comparison of experimental and modelled results indicated that urination behaviour can be simulated with acceptable accuracy and precision using MINDY, a mechanistic and dynamic model of a grazing ruminant. This may reduce the need of expensive and time-consuming animal experiments.

Publications

Bryant, R. H., Miller, M. E., Greenwood, S. L. and Edwards, G. R. “Milk yield and nitrogen excretion of dairy cows grazing binary and multispecies pastures”. *Grass and Forage Science* 72.4 (2017): 806-817. https://doi.org/10.1111/gfs.12274.

Bryant, R. H., Welten, B., Costall, D., Shorten, P. R. and Edwards, G. R. “Milk yield and urinary-nitrogen excretion of dairy cows grazing forb pasture mixtures designed to reduce nitrogen leaching”. *Livestock Science* 209 (2018): 46-53. https://doi.org/10.1016/j.livsci.2018.01.009.

Bryant, R. H., Snow, V., Shorten, P. R. and Welten, B. G. “Can alternative forages substantially reduce N leaching? findings from a review and associated modelling”. *New Zealand Journal of Agricultural Research* 63 (2019): 3-28. https://doi.org/10.1080/00288233.2019.1680395

Chapman, D. F., Edwards, G. R. and Pinxterhuis, J. B. "Plants for dairy grazing systems operating under nitrate leaching limits”. *Proceedings of the New Zealand Society of Animal Production* 74 (2014): 102-107. https://www.cabdirect.org/cabdirect/abstract/20153127418.

Dodd, M. B., Dalley, D. E., Elliott, D. and Wims, C. M. “Establishment year productivity, botanical composition and nutritive value of grass/lucerne/plantain dairy pasture mixtures”. *Journal of New Zealand Grasslands* 79 (2017): 229-235. https://www.grassland.org.nz/publications/nzgrassland_publication_2871.pdf.

Dodd, M., Dalley, D., Wims, C., Elliott, D. and Griffin. A. “A comparison of temperate pasture species mixtures selected to increase dairy cow production and reduce urinary nitrogen excretion*”. New Zealand Journal of Agricultural Research* 62.4 (2019): 504-527. https://doi.org/10.1080/00288233.2018.1518246.

Gregorini, P., Beukes, P. C. and Romera, A. “Screening for forages and foraging managements that reduce nitrogen excretion and methane emissions while maintaining or increasing animal production”. *Journal of Animal Science* 94.Suppl_5 (2016): 328. https://doi.org/10.2527/jam2016-0687.

Gregorini, P. and Edwards, G. R. “Simulating the effect of frequency and timing of Plantago lanceolata allocation on diurnal urination patterns of grazing dairy cows*”. Proceedings of the International Symposium of Nutritional Herbs,* Clermont Ferrand, France (2018, 2-6 September). https://www.cambridge.org/core/services/aop-cambridge-core/content/view/534EC354FE5AB94AA77905505CF6BFB4/S2040470018000146a.pdf/proceedings_of_the_10th_international_symposium_on_the_nutrition_of_herbivores.pdf#page=469.

Gregorini, P., Bryant, R. H., Beck, M. R. and Edwards, G. R. “Plantain: It is not only the dietary content, but also how we graze it”. *New Zealand Society of Animal Production* 78 (2018): 151-160. www.nzsap.org/system/files/proceedings/plantain-it-not-only-dietary-content-also-how-we-graze-it….pdf.

Gregorini, P., Provenza, F. D., Villalba, J. J., Beukes, P. C. and Forbes, M. J. “Diurnal patterns of urination and drinking by grazing ruminants: A development in a mechanistic model of a grazing ruminant, MINDY”. (2019) https://doi.org/10.1017/S0021859617000806.

Gregorini, P., Bryant, R. H., Beck, M. R., Edwards, G. R. “Plantain: It is not only the dietary content, but also how we graze it”. *Proceedings of the New Zealand Society of Animal Production* 78 (2018): 151-160. http://www.nzsap.org/system/files/proceedings/plantain-it-not-only-dietary-content-also-how-we-graze-it%E2%80%A6.pdf.

Minnée, E. M. K., Leach C. M. T. and Dalley D.E. “Substituting a pasture-based diet with plantain (Plantago lanceolata) reduces nitrogen excretion from dairy cows in late lactation”. (2019, Submitted).

Waghorn, G. C., Griffin, A., Bryant, M. and Dalley, D. “Digestion and nitrogen excretion by Holstein/Friesian cows fed grasses with lucerne or lucerne and plantain”. *Animal Production Science* 59.6 (2019): 1070-1080. https://doi.org/10.1071/AN18105.

Plant characterisation, including the digestibility of forages, and the effect of management on pasture composition and drymatter production

A range of field and lysimeter experiments in Canterbury and Waikato were used to test the effect of pasture botanical composition and management strategies on herbage dry matter (DM) yield and quality, N uptake and N leaching. These data were used to produce new APSIM Next Generation models for plantain, chicory, white clover and red clover. Improvements were made to the underlying plant modelling framework to simulate forages and N-fixing/nodulated plants. Diverse mixtures of forages were simulated to understand the limitations of the current modelling platform for plants competing for space and light.

Key results of the work undertaken

- Plantain has similar feed value and milksolids (MS) production potential to perennial ryegrass/white clover pasture when offered as green leafy herbage to dairy cows at a similar herbage allowance.
- Italian ryegrass, prairie grass, high sugar ryegrass and plantain, with lower N fertiliser rates and 4-week regrowth intervals may be used to reduce herbage N intake.
- Legumes were higher in non-protein nitrogen (180 mg/g N), than grasses (111 mg/g N) and herbs (chicory and plantain, 76 mg/g N). Herbs contain N that is more available to be utilised by the animal for growth and production, reducing the amount of N lost as urinary N.

- MS production of cows grazing diverse pastures containing a mixture of legumes, herbs and grasses and managed at high herbage mass in spring was not altered by defoliation management strategies such as pre graze mowing.
- Managing diverse pastures in spring through lenient grazing is a potential management option for an irrigated Canterbury dairy farm system to increase herbage dry matter (DM) production and thereby profitability.
- Forages that tended to have greater herbage crude protein (CP) and non-protein N (NPN) concentrations tended to release more N during maceration.
- Increasing N fertiliser rate applied to ryegrass, chicory and plantain swards also reduced the ratio of fermentable carbohydrate to CP in herbage, which is thought to increase loss of N in urine. The greatest increase in the amount of CP released and greatest decline in the ratio was observed at N rates exceeding 200 kg N/ha/y, coinciding with reductions in herbage mass and leaf growth response to increased rates N fertiliser application.
- Predictions of MS production and N excretion by the MINDY model for cows grazing chicory, ryegrass or plantain, suggests that rates of N fertiliser of 200 kg/ha/y could be the optimal point for MS production before total daily N excretion increases substantially.
- Scenario-based modelling using APSIM showed a 21% and 6% reduction in annual N leaching loss could be achieved by reduced urine N concentration in Waikato and Canterbury regions, respectively.
- Combining all forage, management and systems-based solutions lead to the greatest reductions in nitrate leaching of 59 and 31% for Waikato and Canterbury respectively.
- Direct drilling was more effective than broadcast sowing for establishing plantain in existing pastures. The method of defoliation after sowing (pre-graze mowing or grazing) was not as important as timing of early defoliation in the resulting plantain populations. Early grazing, while seedlings were small enough to avoid defoliation, improved plantain establishment is likely by reducing competition from the pre-existing pasture.

PUBLICATIONS

Box, L. A., Edwards, G. R. and Bryant, R. H. "Milk production and urinary nitrogen excretion of dairy cows grazing perennial ryegrass/white clover and pure plantain pastures". *New Zealand Journal of Animal Science and Production* 76 (2016): 18-21. http://www.nzsap.org/proceedings/milk-production-and-urinary-nitrogen-excretion-dairy-cows-grazing-perennial-ryegrass.

Box, L. A., Edwards, G. R. and Bryant, R. H. "Diurnal changes in the nutritive composition of four forage species at high and low N fertiliser". *Journal of New Zealand Grasslands* 79 (2017): 111-118. https://www.grassland.org.nz/publications/nzgrassland_publication_2853.pdf.

Box, L. A., Edwards, G. R. and Bryant, R. H. "Milk production and urinary nitrogen excretion of dairy cows grazing plantain in early and late lactation". *New Zealand Journal of Agricultural Research* 60.4 (2017): 470-482. https://doi.org/10.1080/00288233.2017.1366924.

Box, L. A., Edwards, G. R. and Bryant, R. H. "Seasonal and diurnal changes in aucubin, catalpol and acteoside concentration of plantain herbage grown at high and low N fertiliser inputs". *New Zealand Journal of Agricultural Research* 62.3 (2017): 343-353. https://doi.org/10.1080/00288233.2018.15055641.

Box, L. A., G. R. Edwards and R. H. Bryant. "In sacco digestion kinetics of plantain and ryegrass-white clover harvested in the morning and afternoon". *New Zealand Journal of Animal Science and Production* 78 (2018): 34-39. http://www.nzsap.org/proceedings/sacco-digestion-kinetics-plantain-and-ryegrass-white-clover-harvested-morning-and.

Box, L. "Can plantain maintain milk production of dairy cows whilst reducing urinary N losses". *Doctoral dissertation, Lincoln University* (2018). https://researcharchive.lincoln.ac.nz/handle/10182/10170.

Bryant, R., Dodd, M., Moorhead, A., Edwards, P. and Pinxterhuis, I. “Effectiveness of strategies used to establish plantain in existing pastures. *Journal of New Zealand Grasslands* 81 (2019):131-137. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/406/63.

Carlton, A., Gardiner, C., Woods, R. and Clough, T. “What really goes on under a urine patch?”. *Proceedings of the South Island Dairy Event*, Dunedin (2018, 25-26 June): 99-104. https://side.org.nz/wp-content/uploads/2018/07/side-proceedings-2018-web.pdf

Chapman, D. F., Lee, J. M., Rossi, L., Edwards, G. R., Pinxterhuis, I. J. B. and Minnee, E. M. K. “White clover: the forgotten component of high-producing pastures?”. *Animal Production Science* 57.7 (2017): 1269-1276. https://doi.org/10.1071/AN16453.

Cichota, R. and Snow, V. “Simulating plant growth in diverse pastures with new forage models in APSIM”. *Agronomy New Zealand* 48 (2018): 77-89. https://www.agronomysociety.org.nz/files/ASNZ_2018_08._APSIM_simulating_plant_growth.pdf.

Cichota, R., McAuliffe, R., Lee, J., Brown, H. E. and Moot, D. J. “Forage chicory model: Development and evaluation”. *Field Crops Research* 246 (2020). 20pp. https://doi.org/10.1016/j.fcr.2019.107633.

Cun, G. S., Edwards, G. R. and Bryant, R. H. “The effect of defoliation severity during late autumn on herbage production, regrowth and nitrogen uptake of diverse pastures in Canterbury, New Zealand”. *Journal of Animal Science* 94.Suppl_5 (2016): 305. https://doi.org/10.2527/jam2016-0640.

Cun, G. S., G. R. Edwards and R. H. Bryant. “Milk production does not benefit from mowing previously lax-grazed diverse pastures”. *New Zealand Journal of Agricultural Research* 61.4 (2018): 468-476. https://doi.org/10.1080/00288233.2017.1411954.

Cun, G. S., Al-Marashdeha, O. and Edwards, G. R. “Whole farm modelling using different grazing management strategies with diverse pastures within an irrigated dairy farm system”. *New Zealand Journal of Animal Science and Production* 78 (2018): 1-5. http://www.nzsap.org/proceedings/whole-farm-modelling-using-different-grazing-management-strategies-diverse-pastures.

Cun, G. “Grazing management strategies of diverse pastures on irrigated dairy farm systems”. *Doctoral dissertation, Lincoln University (*2018). https://researcharchive.lincoln.ac.nz/handle/10182/10613.

Dodd M. B., Moss R. A. and Pinxterhuis J.B. “A paddock survey of on-farm plantain use”. *Journal of New Zealand Grasslands* 81 (2019): 125-130. https://doi.org/10.33584/jnzg.2019.81.408.

Martin, K., Edwards, G., Moir, J., Chapman, D. and Cameron, K. “Herbage dry matter (DM) accumulation and nitrogen concentration of grass, legume and herb species grown at different nitrogen fertilizer rates under irrigation”. *Animal Production Science* 57 (2017): 1283-1288. https://doi.org/10.1071/AN16455.

Martin, K. E., Bryant, R. H., Hodge, S. and Edwards, G. R. “Effect of autumn regrowth interval and nitrogen fertiliser on dry matter yield and plant characteristics of six forage species”. *Journal of New Zealand Grasslands* 79 (2017): 67-72. https://www.grassland.org.nz/publications/nzgrassland_publication_2847.pdf.

Martin, K., “Effects of nitrogen fertiliser and regrowth interval on herbage dry matter yield, chemical composition and nitrogen solubility of alternative pasture forages in irrigated Canterbury conditions”. *Doctoral dissertation, Lincoln University* (2018). https://researcharchive.lincoln.ac.nz/handle/10182/10456.

Minnée, E. M. K., McCready, T. B. and Woodward, S. L. “Herbage production, botanical composition, and survival of perennial ryegrass and tall fescue based swards in simple and diverse species mixtures in a dryland environment”. *Animal Production Science* 57.7 (2017): 1405-1413. https://doi.org/10.1071/AN16475.

Minnée, E. M. K., Waghorn, G. C., Lee, J. M. and Clark, C. E. F. “Including chicory or plantain in a perennial ryegrass/white clover-based diet of dairy cattle in late lactation: Feed intake, milk production and rumen digestion”. *Animal Feed Science and Technology* 227 (2017): 52-61. https://doi.org/10.1016/j.anifeedsci.2017.03.008.

Minnée, E. “The release of nitrogen and carbohydrate from herbage during comminution”. *Doctoral dissertation, Lincoln University* (2017). https://researcharchive.lincoln.ac.nz/handle/10182/10284.

Minnée, E. M. K., Bryant, R. H., Chapman, D. F. and Gregorini, P. “Simulating the intake and nitrogen excretion from cows grazing swards fertilised with increasing rates of nitrogen”. *New Zealand Journal of Animal Science and Production* 78 (2018): 141-145. https://researcharchive.lincoln.ac.nz/bitstream/handle/10182/10791/MInnee%20et%20al%202018%20NZSAP.pdf?sequence=1&isAllowed=y.

Minnée, E. M. K., Waghorn, G. C., Gregorini, P., Bryant, R. H. and Chapman, D. F. “Characteristics of boli formed by dairy cows upon ingestion of fresh ryegrass, lucerne or chicory”. *Animal* 13.6 (2018): 1188-1197. https://doi.org/10.1017/S1751731118002938.

Minnée, E. M. K., Kuhn-Sherlock, B., Pinxterhuis, J. B. and Chapman, D. F. “Meta-analyses comparing the nutritional composition of perennial ryegrass (Lolium perenne) and plantain (Plantago lanceolata) pastures. *Journal of New Zealand Grasslands* 81 (2019): 117-123. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/402/61.

Woods, R., Carlton, A., Martin, K., Box, L. and Cun, G. “Practical options for reducing the environmental impacts of intensive, forage-based dairy systems”. South Island Dairy Event, Lincoln (2017, 26-28 June): 201-211. https://side.org.nz/wp-content/uploads/2017/06/5.4-Practical-options-for-reducing-environmental-impacts-Racheal-Bryant.pdf.

N uptake and leaching in pure swards and diverse pastures, effects of pasture management

Lysimeter and small outdoor plot trials were carried out to determine the effect of irrigation management (frequency, timing, level of water stress) and gibberellic acid application on nitrate leaching from multi-species and standard perennial ryegrass/white clover pastures. The impact of plant species on soil C and N transformations (mineralisation and nitrification) and legume N_2 fixation was measured using ^{15}N tracer studies on pastures.

Key results of the work undertaken

- Italian ryegrass and the late-heading date and late-season maturing perennial ryegrass cultivar, One 50, were found to be the most effective pasture grass options to reduce N leaching loss.
- Italian ryegrass leached 33 to 46% less nitrate-N than Tyson, AberDart, Tyson-Italian and Arrow swards.
- Italian ryegrass swards took up 1.2 to 1.4 times more N than any other grass type reducing the amount of N available for leaching.
- Italian ryegrass produced significantly less drainage: 31-46% less than all other pure swards.
- Drilling Italian ryegrass into established perennial ryegrass swards did not significantly reduce nitrate leaching losses.
- Large leaching losses occurred from urine applied to lucerne (> 200 kg N/ha) due to low plant uptake during the autumn-winter drainage period.
- Plantain reduced N leaching losses by 15% in summer and by 30 – 50% in winter (average 39%) compared to perennial ryegrass grown in free draining volcanic ash soil.
- Allied research has shown plantain can affect soil microbial biota and reduce nitrous oxide emissions from urine excreted on soil.
- Mechanisms influencing reduced N leaching when using plantain appear to be associated with a combination of urine N concentration, plant N uptake and nitrification inhibition.

- Compared with perennial ryegrass/white clover, N leaching from perennial ryegrass/white clover/plantain was 82% and 74% lower when standardised urine was applied in December and February, respectively. Growth of ammonia oxidising bacteria was significantly reduced with plantain in the mixture, indicating a biological nitrification inhibiting effect.
- Compared with perennial ryegrass/white clover, N leaching from Italian ryegrass/white clover/plantain was reduced by 46% when using a standardised urine N load, due to greater cool-season growth with water and N uptake, and by 89% when using urine from cows grazing these pastures, due to the additional effect of reduced urinary N concentration.
- Irrigation system (simulated pivot, rotorainer and flood irrigation, with the same total amount of water applied over the dry season) did not affect N leaching.
- A comparison of N leaching from a single urine application to monocultures of perennial ryegrass, plantain or lucerne showed that plantain exhibited large seasonal variation in its efficacy to reduce urine-N leaching relative to ryegrass (ranging from 15% to 50% reduction for summer or winter urine applications, respectively) with an overall reduction of 39% (53 and 87 kg N/ha leached for plantain and ryegrass, respectively). Leaching from lucerne was consistently high (>200 kg N/ha).
- Application of gibberellic acid had no effect on N leaching losses, DM yield, or N uptake of perennial ryegrass/white clover, Italian ryegrass or Lucerne treated with 700 kg N/ha urine.
- Annual N_2 fixation was 3-fold higher in mixed (white clover, lucerne, perennial ryegrass, chicory and plantain) relative to standard perennial ryegrass/white clover pasture (averaged 193 vs. 75 kg N/ha/year, respectively) due to higher legume yield in mixed pastures. Both pasture types showed an exponential decline in annual N_2 fixed as fertiliser-N input increased.
- Laboratory soil incubation studies with urine (equivalent to 300 and 600 kg N/ha) applied to ryegrass or plantain soil showed that plantain inhibits nitrification of urinary-N over a short-period (<28 days) with the level of inhibitory effect decreasing over time.
- Detailed ^{15}N-isotope studies with ryegrass and plantain monocultures by two fertiliser-N rates (0 vs. 500 kg N/ha/year) showed evidence that plantain manipulates short-term nitrogen processes controlling plant N availability.

Publications

Carlton, A. J., Cameron, K. C., Edwards, G. R., Di, H. J. and Clough, T. J. "The effect of optimum vs. deficit irrigation on plant nitrogen uptake and nitrate leaching loss from soil". In: *Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2016). https://www.massey.ac.nz/~flrc/workshops/16/Manuscripts/Paper_Carlton_2016.pdf.

Carlton, A. J. "The effect of diverse forage species and irrigation management on plant nitrogen uptake and nitrate leaching losses". *Doctoral dissertation, Lincoln University* (2018). https://researcharchive.lincoln.ac.nz/handle/10182/8950.

Carlton, A. J., Cameron, K. C., Di, H. J., Edwards, G. R. and Clough, T. J. "Nitrate leaching losses are lower from ryegrass/white clover forages containing plantain than from ryegrass/white clover forages under different irrigation". *New Zealand Journal of Agricultural Research* 62 (2019): 150-172. https://doi.org/10.1080/00288233.2018.1461659.

Maxwell, T. M. R., McLenaghen, R. D., Edwards, G. R., Hong, D. J. and Cameron, K. C. "Italian ryegrass swards reduce N leaching via greater N uptake and lower drainage over perennial ryegrass cultivars varying in cool season growth rates". *New Zealand Journal of Agricultural Research* 1.14 (2018): 69-82. https://doi.org/10.1080/00288233.2018.1426615.

Welten, B. G., Ledgard, S. F, Judge, A. A., Sprosen, M. S., McGowan, A. W. and Dexter, M. M. "Efficacy of different temperate pasture species to reduce nitrogen leaching from cattle urine applied in different seasons: A soil lysimeter study". *Soil Use and Management Journal* (2019, 31 March). https://doi.org/10.1111/sum.12512.

Welten, B., Ledgard, S., Sprosen, M., Judge, A. and Waugh, D. "Nitrogen fixation by white clover and lucerne in contrasting temperate pasture species mixtures with varying nitrogen fertiliser input". *New Zealand Journal of Agricultural Research* (2019, Submitted).

Woods, R. R., Cameron, K. C., Edwards, G. R., Di, H. and Clough, T. J. "Does gibberellic acid reduce nitrate leaching losses from animal urine patches?". In: *Integrated nutrient and water management for sustainable farming. Currie, LD, Singh R (Eds.). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2016). http://www.massey.ac.nz/~flrc/workshops/16/Manuscripts/Paper_Woods_2016.pdf.

Woods, R. R., Cameron, K. C., Edwards, G. R., Di, H. J. and Clough, T. J. "Effects of forage type and gibberellic acid on nitrate leaching losses". *Soil Use and Management* 32.4 (2016): 565-572. https://doi.org/10.1111/sum.12297.

Woods, R. R., Cameron, K. C., Edwards, G. R., Di, H. J. and Clough, T. J. "Reducing nitrogen leaching losses in grazed dairy systems using an Italian ryegrass-plantain-white clover forage mix". *Grass and Forage Science* 73.4 (2017): 878–887. https://doi.org/10.1111/gfs.12386.

Woods, R. R., Cameron, K. C., Edwards, G. R., Di, H. J. and Clough, T. J. "^{15}N recoveries from urine patches on different forage types". Plant and Soil. 417.1-2 (2017): 453-465. https://doi.org/10.1007/s11104-017-3270-5.

Woods, R. "The effect of alternative forage species and gibberellic acid on nitrate leaching". *Doctoral dissertation, Lincoln University* (2017). https://hdl.handle.net/10182/8271.

Fate of N in urine patches

This work was supported with co-funding from the Strategic Science Investment Fund (SSIF) of AgResearch.

Lysimeters and small plots were used to measure N uptake and nitrate leaching from applied urine for various pasture species and mixed-species pastures. Differences in urine patch size and associated edge-effects were evaluated to identify urine-specific effects of pasture species mixture on nitrate leaching.

APSIM simulation was developed to represent the urine patch edge effects of the pasture species. The new and improved modules were validated against data collected in the field and lysimeter trials. Potential impact of diverse pastures to reduce leaching while maintaining or improving production at the paddock scale was examined using the validated modelling system and information generated in grazing trials regarding urine patch characteristics.

Key results of the work undertaken

- N offtake from the urine patch was greater with plantain than with standard pasture; however, the relative contribution to uptake from the wetted area and surrounding edge was the same for both species. Most (>90%) of the apparent offtake of urine N by plantain and standard pastures was within 20cm of the edge of the urine patch.
- 30-40% of the pasture N uptake from urine deposited on the wetted zone came from outside the wetted zone, with the edge contribution larger in small urine patches. Lysimeters with a confined edge may potentially underestimate pasture N uptake.

- Detailed model (HYDRUS 2-D and APSIM) of a single urine patch including water and N flow beyond the wetted edges of a urine patch, suggests that typically about 0.1 m spread might be expected. This was consistent with independent experimental work.
- The vegetation model AgPasture was updated, fully documented and converted to the APSIM Next Generation framework. It is currently in peer review and should be in release in the next month.
- Information from the patch-scale modelling was used to set some key parameters in a new paddock-scale model that explicitly incorporates urine patches.
- The paddock-scale model was used to investigate the likely improvement in leaching from diuretics in the diet. Although a lower urine N concentration reduced the N load in urine patches, it also led to a larger area of the paddock covered by urine and a greater occurrence of overlapping urine patches. Therefore, the effectiveness of the diuretic decreased as stocking rate rose and high rates of N fertiliser were used.

PUBLICATIONS

Badham, J., Elsawah, S., Guillaume, J. H. A., Hamilton, S. H., Hunt, R. J., Jakeman, A. J., Pierce, S. A,. Snow, V. O., Babbar-Sebens, M., Fu, B., Gober, P., Hill, M. C., Iwanaga, T., Loucks, D. P., Merritt, W. S., Peckham, S. D., Richmond, A. K., Zare, F., Ames, D., Bammer, G. "Effective modeling for Integrated Water Resource Management: A guide to contextual practices by phases and steps and future opportunities, *Environ. Model. Softw*., 116 (2019) 40-56. https://doi.org/10.1016/j.envsoft.2019.02.013.

Balvert, S. and Shepherd, M. "Does size matter - the effect of urine patch size on pasture N uptake". In: *Moving farm systems to improved attenuation. Currie LD, Burkitt LL (Eds.). Occasional Report No. 28. Fertilizer and Lime Research Centre,* Massey University, Palmerston North, New Zealand. (2015). http://www.massey.ac.nz/~flrc/workshops/15/Manuscripts/Paper_Balvert_2015.pdf.

Cichota. R., Vogeler, I., Snow, V., Shepherd, M., McAuliffe, R. and Welten, B. "Lateral spread affects nitrogen leaching from urine patches". *Science of Total Environment* 635 (2018): 1392-1404. https://doi.org/10.1016/j.scitotenv.2018.04.005.

Fitton, N., Bindi, M., Brilli, L., Cichota, R., Dibari, C., Fuchs, K., Huguenin-Elie, O., Klumpp, K., Lieffering, M., Lüscher, A., Martin, R., McAuliffe, R., Merbold, L., Newton, P., Rees, R. M., Smith, P., Topp, C. F. E. and Snow, V. "Modelling biological N fixation and grass-legume 1 dynamics with process-based biogeochemical models of varying complexity". *European Journal of Agronomy* 106 (2019): 58-66. https://doi.org/10.1016/j.eja.2019.03.008.

Holzworth, D. P., Huth, N. I., Fainges, J., Brown, H., Zurcher, E., Cichota, R., Verrall, S., Herrmann, N. I., Zheng, B. and Snow, V. "APSIM Next Generation: Overcoming challenges in modernising a farming systems model, *Environmental Modelling & Software* 103 (2018): 43-51. https://doi.org/10.1016/j.envsoft.2018.02.002.

Shepherd, M. A. and Carlson, W.T. "Urine patch size and nitrogen load: effects on nitrogen uptake from the urine patch in plantain and ryegrass/white clover pastures". *Journal of New Zealand Grasslands* 80 (2018): 195-200. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/321.

Shepherd, M., Shorten, P. and Carlson, B. "The contribution of the urine patch edge to pasture-N uptake". *New Zealand Journal of Agricultural Research* (2018, Submitted).

Snow, V. O., Eckard, R. J., Rotz, C. A., Johnson, I. R. and Hutchings, N. J. "The challenges of incorporating urine and dung patches in process-based modelling of grazed agricultural systems". In: *Ames DP, Quinn NWT, Rizzoli AE (Eds.) International Environmental Modelling and Software Society (iEMSs), 7th Intl. Congress on Env. Modelling and Software*, San Diego, CA, USA. (2014). https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1088&context=iemssconference.

Snow, V. O., Rotz, C. A., Moore, A. D., Martin-Clouaire, R., Johnson, I. R., Hutchings, N. J. and Eckard, R. J. "The challenges - and some solutions - to process-based modelling of grazed agricultural systems".

Environmental Modelling & Software 62 (2014): 420-436. https://doi.org/10.1016/j.envsoft.2014.03.009.

Snow, V. O., Cichota, R., McAuliffe, R. J., Dynes, R. A., Vogeler, I., Ledgard, S. F. and Shepherd, M. A., “What is “sufficient” complexity when modelling urine patches in grazed pastures?”. In: *Syme, G., Hatton MacDonald, D., Fulton, B., Piantadosi, J. (Eds.), MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand* ISBN: 978-0-9872143-7-9 (2017, December): 22–28. http://www.mssanz.org.au/modsim2017/Keynote/snow.pdf.

Snow, V. O., Cichota, R., McAuliffe, R. J., Hutchings, N. J. and Vejlin, J. l. “Increasing the spatial scale of process-based agricultural systems models by representing heterogeneity: The case of urine patches in grazed pastures”. *Environmental Modelling & Software* 90 (2017): 89-106. https://doi.org/10.1016/j.envsoft.2017.01.005.

Snow, V. O., Meenken, E., Cichota, R., Holzworth, D. P. and Dynes, R. A. “Are diuretic-based mitigations of leaching and N_2O emissions from urine patches effective at farm scales and higher stocking rates”. (2020, submitted).

Forage and conserved feed crops and crop management systems that enhance the productivity and N use efficiency of arable and pastoral sector farms

High-nutritive value, low-N forage and conserved feed crops can maintain or increase the performance of livestock while reducing the excretion of N in animal urine and associated N losses.

Integrated soil, crop and effluent management practices for the production of forage and conserved feed crops can increase the N use efficiency of continuous cropping, mixed and livestock farms, and significantly reduce N losses associated with either the production or consumption of these feeds.

Key components of high nutritive value, low N forage and conserved feed crops for livestock

A database of crop quality characteristics has been developed and populated with available NZ and overseas data. Meta-analysis of these data identified the key nutritive components of forage and feed crops that explain variability in livestock performance and returns of N in excreta. Data were used in the mechanistic animal performance model (MOLLY) to identify the key crops and crop combinations that maintain or increase livestock performance and reduce partitioning of N into urine and methane emission. Crops identified from these livestock modelling experiments were used in small plot crop management trials and large plot grazing trials.

Key results of the work undertaken

- A database comprising forage quality tests and associated field management metadata was derived from literature, FRNL trials and historical crop sampling. At the time of analysis for a scientific manuscript, the dataset comprised 2770 samples, representing 71 crops or crop mixes. Since then, more crop data has been added, and the database has been extended with pasture quality data. This is a valuable resource base for future crop and pasture quality reference.
- The feed quality database comprises a framework for assessing indices for crude protein (CP) and total soluble carbohydrates (SSS) content and classifying diet suitability for lactating and non-lactating dairy animals, with or without an environmental weighting to achieve minimised N leaching.
- Assessment of the crop quality database collated in FRNL, showed that rape, turnips, and whole crop silages featured strongly in pre-defined critical ranges for lactating dairy cows of 16-20% crude protein (CP) and >25% soluble sugars and starch (SSS).
- Other feeds with high SSS and low CP concentrations such as fodder beet, maize silage, wheat and barley grains are useful dietary supplements but are below the CP requirements for lactation if fed alone. Additional protein from pasture, pasture silage or legume supplements (peas, tick beans, clovers, lucerne) is necessary to meet requirements.
- For non-lactating cows with a CP requirement of 10-16%, whole crop cereal silages, brassicas (turnips, kale, swedes) and legumes (peas and tick beans) are the best fit. Cereal grains, maize silage and fodder beet meet the non-lactating feed requirements, but these are best incorporated into a mixed diet.
- N fertiliser was the only agronomic management factor that could consistently be used to adjust the quality for animal requirements. Factors such as delayed sowing and plant population had minor systematic influence on quality. Much of the variation in quality was accounted for by crop selection and/or the environment in which the crop was grown.
- The DairyNZ Whole Farm Model with the animal model Molly was used to screen 11,526 binary diets comprising 51 feeds (forages and grains) combined in different proportions. Combinations with the best

possible compromise between urinary N excretion, methane emission and milksolids production were identified. Fodder beet and cereals featured strongly.

Publications

Chakwizira, E., Fletcher, A. L., Johnstone, P. R., de Ruiter, J. M., Pearson, A. J. and Parker, M. "Maize silage-winter crop sequences that maximise forage production and quality". *New Zealand Journal of Agricultural Research* 62.1 (2017): 1-22. https://doi.org/10.1080/00288233.2017.1415943.

Dalley, D.E., Malcolm, B. J., Chakwizira, E. and de Ruiter, J. M. "Range of quality characteristics of New Zealand forages and implications for reducing the nitrogen leaching risk from grazing dairy cows". *New Zealand Journal of Agricultural Research* 60.3 (2017): 319-332. https://doi.org/10.1080/00288233.2017.1345762.

de Ruiter, J. M., Malcolm, B. J., Chakwizira, E., Johnstone, P., Maley, S., Arnold, N. and Dalley, D. E. "Crop management effects on supplementary feed quality and crop options for dairy feeding to reduce nitrate leaching". *New Zealand Journal of Agricultural Research* 62.3 (2019): 369-398. https://doi.org/10.1080/00288233.2018.1508042.

Gregorini, P., Beukes, P. C., Dalley, D. and Romera, A. J. "Screening for diets that reduce urinary nitrogen excretion and methane emissions while maintaining or increasing production by dairy cows". *Science of the Total Environment* 551–552 (2016): 32–41. https://doi.org/10.1016/j.scitotenv.2016.01.203.

Performance and N partitioning response of livestock to high nutritive value, low N feed crops

This work was supported with co-funding from the Strategic Science Investment Fund (SSIF) of AgResearch.

Animal metabolism stall trials were conducted to define N partitioning, rumen turnover, and digestive responses of livestock to fodder beet, a key crop identified in the work summarised above. Amino acid concentrations in blood plasma was determined to identify potential limitations in amino acid supply for dairy cows to maintain milk production while reducing N excretion.

Key results of the work undertaken

- Fodder beet feeding reduced urinary N excretion compared with that observed from most good quality pasture diets.
- A diet of 65% fodder beet and 35% pasture silage supplied adequate nutrition for **non-lactating dairy cows** although there was some risk of acidosis. A diet containing 85% fodder beet with barley straw resulted in low dry matter intake, poor rumen function and negative N balance compromising both animal nutrition and welfare. Straw should not be fed as a sole fibre source with fodder beet because of the risk of inadequate nutrition and high incidence of acidosis.
- Substitution up to 45% of a pasture diet DM with fodder beet had no detrimental effects on the health or production of **cows in late lactation** but 60% fodder beet resulted in clinical acidosis. When offered at less than 23% of diet dry matter (DM), fodder beet increased DM digestibility but this trend was reversed when >45% of the diet DM was fodder beet. Caution is required when offering diets with greater than 40% fodder beet to ensure they contain sufficient N, phosphorus and sulphur.
- Variations in the N:creatinine ratio over 24 h with each diet as well as lower measured creatinine excretion compared to published values indicate a likelihood of substantial errors in the prediction of daily urinary excretion if using spot sampling.
- Feeding fodder beet alters the profile of amino acids to the lactating dairy cow, as demonstrated by the reductions in the plasma concentrations in amino acids such as arginine and glutamine. The use of fodder beet as a tool to manage nitrogen excretion needs to take these findings into account, because

these amino acids are involved in critical development functions, such as fetal development and intestinal integrity.

Publications

Dalley, D. "The foibles of fodder beet and other forage crops – animal and environmental considerations for successfully feeding forage crops". *South Island Dairy Event*, Lincoln University, Lincoln (2016, 26-28 June). https://side.org.nz/wp-content/uploads/2016/06/1.1-The-Foibles-of-Fodder-Beet-and-Other-Forage-Crops.pdf.

Pacheco, D., Waghorn, G. and Dalley, D. "BRIEF COMMUNICATION: Plasma amino acid profiles of lactating dairy cows fed fodder beet and ryegrass diets". *Proceedings of the New Zealand Society of Animal Production* 76 (2016): 62-64. http://www.nzsap.org/system/files/proceedings/%2363%20Pacheco.pdf.

Pacheco, D., Muetzel, S., Lewis, S., Dalley, D., Bryant, M. and Waghorn, G. C. "Rumen digesta and products of fermentation in cows fed varying proportions of fodder beet (*Beta vulgaris* L.) with fresh pasture or silage or straw". *Animal Production Science* 60 (2020): 524-534. https://www.publish.csiro.au/AN/AN18002.

Waghorn, G. C., Collier, K., Bryant, M. and Dalley, D. "Feeding fodder beet (Beta vulgaris L.) with either barley straw or pasture silage to non-lactating dairy cows". *New Zealand Veterinary Journal* 66.4 (2018): 178-185. https://doi.org/10.1080/00480169.2018.1465484.

Waghorn, G. C., Law, N., Bryant, M., Pacheco, D. and Dalley, D. "Digestion and nitrogen excretion by Holstein/Friesian cows in late lactation fed ryegrass pasture with fodder beet". *Animal Production Science* 59 (2018): 1261-1270. https://doi.org/10.1071/AN18018.

Effects of urine derived from high nutritive value, low N feed crops on soil N transformations

Urine was collected from cows in the various animal trials described above, with a range of composition. The dairy cows were fed the standard high-N reference diet and high nutritive value, low-N feeds. Concentrations of allantoin (a chemical constituent of ruminant urine) were determined in the cow urine and a methodology for measuring allantoin in soil samples was developed. Urine was applied to soil and the half-life of allantoin was determined.

Key results of the work undertaken

- Allantoin is broken down rapidly in soil, with a half-life of only around 2 to 3 hours.
- In a small range of urine samples from animals fed plantain, the total N concentration was lower than from animals fed standard ryegrass/clover pastures. There was also a tendency for a lower allantoin content.
- Given the rapid degradation of allantoin observed in the soil, we disproved our hypothesis that the concentration of allantoin in urine may be sufficient to modify the activity of soil micro-organisms involved in transforming N deposited in the urine of grazing livestock.

Publications

Peterson, M., Fraser, P. M. and Curtin, D. "A Plant & Food Research report prepared for: Dairy NZ. Milestone No. 67732. Contract No. 32051. Job code: P/442056/03. SPTS No. 13193*". Commissioned report: CS1.2.6* (2016).

Predicting soil N mineralisation for cropping soils

This work was completed with funding from the Strategic Science Investment Fund (SSIF) of Plant & Food Research.

A new laboratory test for predicting the potentially mineralisable N (PMN) in soils was developed and verified across a wide range of arable and pastoral soils (>130 sites) in New Zealand. Key soil processes, critical C and N pools and dominant environmental factors (temperature, moisture, pH) that regulate the accumulation, transformation and mineralisation of soil organic matter were accounted for. The methodology supports crop management to optimise N supply and minimise the risk of N leaching.

Key results of the work undertaken

- The new lab test is a significant improvement on the current anaerobically mineralisable N (AMN) test offered by commercial laboratories. The research team is currently working with three major commercial testing laboratories in New Zealand to calibrate the test and make it available to clients.
- The new test also has applications to state-of-environment monitoring by Regional Councils. Discussion of our findings with members of the Land Monitoring Forum led to an Envirolink project where the new test was evaluated for its use in soil quality monitoring.
- Results from Canterbury-based field trials showed that the test, when coupled with local environmental data, can be used to predict the N mineralised under field conditions based on an N balance approach.
- The initial field trial results led to a Sustainable Farming Fund project that is focussed on validating on-farm applications of the test to improve fertiliser forecasting across a wider range of soil, crops and climates. The SFF project is co-funded by the Foundation for Arable Research, the VR&I board of Horticulture New Zealand, three commercial testing labs and three regional councils.
- Results from a long-term field trial confirmed that N mineralisation was the predominant source of plant available N and an important source of N for the additional dry matter grown in response to superphosphate (P) fertilisation.

Publications

Curtin, D., Beare, M. H., Lehto, K., Tregurtha, C., Qiu, W., Tregurtha, R. and Peterson, M. "Rapid Assays to Predict Nitrogen Mineralization Capacity of Agricultural Soils". *Soil Science Society of America Journal* 81.4 (2017): 979-991. https://doi.org/10.2136/sssaj2016.08.0265.

Curtin, D., Beare, M. H., Qiu, W. and Tregurtha, C. “Nitrogen cycling in soil under grass-clover pasture: influence of long-term inputs of superphosphate on N mineralisation”. *Soil Biology and Biochemistry* 130 (2019): 132-140. https://doi.org/10.1016/j.soilbio.2018.12.003.

Protocol for using large area lysimeters to accurately quantify field scale drainage and N leaching

This work was supported with co-funding from the Strategic Science Investment Fund (SSIF) of Manaaki Whenua – Landcare Research.

The performance of large area lysimeters was validated by measuring and comparing drainage patterns and N leaching following urinary N applications. Operational limits with this methodology were identified.

Key results of the work undertaken

- Accuracy of field scale monitoring of leaching under grazed pasture can vary greatly depending on factors such as urine patch concentration and spatial distribution, and the type and number of monitoring devices.

- Spatial statistical modelling can enable scenario analysis of different experimental options for monitoring field scale leaching and field trials to test the effect of management or mitigation options on leaching.
- Large area lysimeters can provide an integrated measure of leaching and can be constructed of sufficient size to contain multiple urine patches, non-urine areas, as well as multiple plants of different fodder crops.

PUBLICATIONS

Balance, A. and Carrick, S. "The science of stony soils and water". *Rural Media: RadioNZ- Our Changing World* (2015, 8 October). http://www.radionz.co.nz/national/programmes/ourchangingworld/audio/201773468/science-of-stony-soils-and-water.

Carrick, S. "Kiwi inventiveness plays role in soil experiment". *Rural Media: DairyNZ website news item* (2015, 28 July). http://www.dairynz.co.nz/news/latest-news/kiwi-inventiveness-plays-role-in-soil-experiment/.

Carrick, S., Rogers, G., Cameron, K., Malcolm, B. and Payne, J. "Testing large area lysimeter designs to measure leaching under multiple urine patches". *New Zealand Journal of Agricultural Research* 60.2 (2017): 205-215. https://doi.org/10.1080/00288233.2017.1291527.

Production of high nutritive value, low N forages and crops that maintain animal performance and mitigate N losses

Large plot crop production and livestock feeding trials were conducted in Canterbury and Waikato to validate selected crops identified with the database analysis and modelling described above. Animal performance and urinary N excretion was assessed. The benefit of crop production practices and the use of catch crops following these grazed crops for reducing nitrate leaching was verified in small plot and lysimeter trials. The combined knowledge from the lysimeter, small and large plot trials was summarised in crop management guidelines for fodder beet and catch crops.

KEY RESULTS OF THE WORK UNDERTAKEN

FEED QUALITY OF CROPS

- In Waikato, cut & carry crops grown for supplement can reduce the N content of soil ahead of winter. Ideal crops for cut & carry include maize and Sudan x Sudan as the cumulative N uptake was between 250 and 300 kg N/ha.
- Maize and fodder beet were the best options for producing high carbohydrate and low N forage to complement base diets of ryegrass. Sudan x Sudan responded well to successive monthly grazing, however in this situation N returns from animal excretion added to the N loading of the soil. This is also the case with other grazed crops such as rape, fodder beet and Italian ryegrass.
- A combination of these crops in a farm system introduces flexibility to take advantage of periods of wet weather, or pasture shortage due to drought. Autumn utilisation of fodder beet along with conserved maize or Sudan hybrid can bridge periods of feed shortage, while minimising the N impacts if fed on non-critical source areas.
- Crude protein content of maize (6%), Sudan hybrid (11-14%), fodder beet (7-8%) and rape (9-19%) varied depending on the harvest/grazing time but these crops mostly provided low-N feed for reducing total protein/N intake by grazing animals.

Catch crops

- Paddock-scale trials in Waikato and Canterbury showed that late autumn and winter-sown oat and Italian ryegrass catch crops can reduce the risk of N leaching after fodder beet grazing. In Waikato, oats performed better than Italian ryegrass, due to a bigger sink size for N, supporting smaller plot experiments described below. Overall, yields and the amounts of N taken up by catch crops was in close agreement with those of the smaller plot experiments.
- In the Waikato experiment it was shown that the biomass produced by the oats (9.5 t DM/ha on average) compensated for any loss in production during the establishment of pasture post oat harvest (October), with 6.4 t DM/ha more feed produced overall than Italian ryegrass.
- Lysimeter experiments run over two years showed that N leaching losses from winter-deposited urine patches (simulated fodder beet grazing) could be reduced by 33–44% with an oat catch crop under Balmoral soil, and 12–59% under Templeton soil. Catch crops reduced N leaching more consistently under Balmoral soil compared with Templeton, due to absolute leaching losses being higher under Balmoral. Seasonal effects were largely responsible for the varying degree of efficiencies of catch crops on Templeton soil.
- In the same lysimeter experiment, oat catch crops also reduced N leaching from autumn urine deposition after simulated fodder beet grazing, but to a lesser extent (17 and 15% under Balmoral and Templeton soil, respectively) than those following winter grazing scenarios. This is attributed to the timing and amount of rainfall and soil temperatures, in relation to when the catch crop establishes and starts taking up N. For instance, urine deposited in early May nitrifies at higher rates than that deposited in winter, due to warmer soil temperatures. However, early May-sown catch crops grow slowly over the cool winter months, restricting its ability to take up N. Catch crops generally begin to be effective at reducing soil N in early spring (around early September), by which time most of the autumn-deposited urine N is already leached. Autumn urine applications are also exposed to a greater amount of rainfall/drainage (mode of leaching), compared with later depositions in winter.
- The lysimeter experiment also indicated that more than half the amount of N leached from winter urine (55–74%) occurred during the spring months, coinciding with peak nitrate concentrations, and when catch crops were actively taking up N (i.e. being most effective at reducing N leaching).
- A paddock-scale leaching experiment using an array of buried suction cups and monolith lysimeters for measuring drainage volume, showed that leaching losses after winter fodder beet grazing by non-lactating dairy cows were not significantly reduced by an oats catch crop under particularly wet weather conditions in winter. These weather conditions resulted in a significant delay in when the oats were able to be drilled. These findings support earlier work that highlighted the importance of sowing catch crops early. A repeat run of the trial in the next year showed significant reductions in N leaching in spring, due to an earlier establishment of the oats compared with that in the first year.

Animal grazing trials

- An initial grazing experiment showed the amount of urine-N excreted was significantly lower from cows consuming a fodder beet/pasture silage diet compared to a maize/fresh pasture diet (estimated 90 vs. 173 g N/cow/day). This was largely due to lower N intake. Lower urine N concentration reduced N loading per urinary event in fodder beet vs maize in diets.
- A follow-up grazing experiment showed that fodder beet fed to late-lactation dairy cows in place of maize silage at 25% of the diet (with pasture) improved milk solids production but did not reduce urine N excretion. Increasing dietary allocations of fodder beet to 45% (with pasture) reduced urine N excretion, but at the expense of milk solids production (particularly milk fat yield), attributed to subclinical rumen acidosis.

- Liver markers of stress did not increase during the cows' transition to fodder beet, and liver function markers in the blood were minimally affected on 8 kg DM fodder beet per cow per day. Cell protective mechanisms increased in the liver, but only in the short term.
- The transition of non-lactating cows onto a fodder beet diet can be managed to minimise the negative effects of the high sugar intake.

Publications

Dalley, D., Waugh, D., Griffin, A., Higham, C., de Ruiter, J. and Malcolm, B. "Productivity and environmental implications of fodder beet and maize silage as supplements to pasture for late lactation dairy cows". *New Zealand Journal of Agricultural Research* 63 (2019): 145-164. https://doi.org/10.1080/00288233.2019.1675717.

de Ruiter J., Malcolm, B. and Dalley, D. "Variation in Quality of Temperate Crops with High-Carbohydrate and Low-Nitrogen Content for Dairy Cow Lactation and Winter Feeding". *Proceedings of the XV European Agronomy Society Conference 2018* (2018, 27-31 August): 83-84 (Abstract #PS-9.3-05). http://www.esa-congress-2018.ch/wp-content/uploads/2018/08/ESA2018_AbstractBook_A4-1.pdf.

Grala, T. M., Handley, R. R., Phyn, C. V. C., Roche, J. R. and Dalley, D. E. "A quantitative case study assessment of changes to hepatic metabolism from nonlactating grazing dairy cows consuming a large proportion of their diet as fodder beet". *Journal of Dairy Science* 102.9 (2019): 8559-8570. https://doi.org/10.3168/jds.2018-16009.

Malcolm, B., Carey, P, Teixeira, E, Johnstone, P., Maley, S. and de Ruiter, J. "Potential of catch crops to reduce nitrogen leaching in New Zealand winter grazing systems". *Journal of New Zealand Grasslands* 80 (2018): 207-214. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/331.

Malcolm, B., de Ruiter, J., Dalley, D., Johnstone, P., Dellow, S., Arnold, N. and Waugh, D. "Using catch crops to mitigate nitrate leaching following autumn grazed fodder beet in Waikato". *New Zealand Society of Soil Science Conference*, Napier (2018, 5 December). https://www.researchgate.net/publication/339886691_Using_catch_crops_to_mitigate_nitrate_leaching_following_autumn_grazed_fodder_beet_in_Waikato

Malcolm, B. J., de Ruiter, J. M., Dalley, D. E., Carrick, S., Waugh, D., Arnold, N. P., Dellow, S. J., Beare, M. H., Johnstone, P. R., Wohlers, M., Welton, B. and Horrocks, A. J. "Catch crops and feeding strategy can reduce the risk of nitrogen leaching in late lactation fodder beet systems". *New Zealand Journal of Agricultural Research* 63 (2020): 44-64. https://doi.org/10.1080/00288233.2019.1704422.

Malcolm, B.J. , Cameron, K.C. , Beare, M.H., Carrick, S. , Payne, J. , Maley, S. , Di, H.J , Richards, K. , Dalley, D.E. , de Ruiter, J.M. "Effect of oat catch crops on nitrogen leaching losses following fodder beet grazing on two contrasting soils in New Zealand". (2020, in preparation).

Malcolm, B., Cameron, K., Beare, M., Carrick, S., Payne, J., Maley, S. Di, H., Richards, K. and de Ruiter, J. "Effect of catch crops on nitrogen leaching losses following cool season forage crop grazing in New Zealand". *Proceedings of the 2020 International Nitrogen Initiative*, Berlin, Germany (2020, submitted).

High production, high N use efficiency crop sequences with forage and conserved feeds

This work was supported with co-funding from the Strategic Science Investment Fund (SSIF) of Plant & Food Research.

A multi-crop simulation tool was developed in APSIM to enable testing crop combinations that optimise the trade-offs between high yield, high nutritive value and low environmental footprint. This tool can also inform strategic and tactical N management decisions, such as planting and harvest dates, and amount and timing of fertiliser or effluent N supply.

A meta-analysis of published data and crop sequence simulations with APSIM identified options to maximise the N use efficiency of forage and conserved feed crops grown in sequence with arable crops. This included crops to mop up early spring mineral N loads following winter grazing of crops and early autumn sown crops to mop up residual N from fertiliser and N mineralisation following summer crops.

Multi-year field trials in Canterbury and Waikato validated and demonstrated the most promising crop sequences identified. Results informed the crop management guidelines for fodder beet and catch crops.

KEY RESULTS OF THE WORK UNDERTAKEN

- New FRNL field data and modelling concepts were used to develop two new biophysical models within the modern APSIM Next Generation (APSIM-X) platform. Specifically, Fodder Beet and Oats APSIM-X models are now officially released by the APSIM initiative and freely available through their repository.
- The new APSIM-X models were used to investigate FRNL relevant questions. Key new insights using these models include:
  - Winter sown catch crops after fodder beet, a new usage of catch crops, shows potential for reduction in N leaching but results are more impacted by weather variability than conventional autumn-sown catch crops.
  - The ranges of catch crop effectiveness to reduce N leaching differs across NZ climate zones and soils, so spatial analyses are relevant.
  - Best management (e.g. early sowing) enhances catch crops effectiveness in winter grazing systems, as for autumn-sown conventional systems, although the maximum effectiveness achieved is lower for winter-sown crops.
  - An estimate of catch crop effectiveness for four regions, four sowing dates and three rainfall categories was produced using the new model capability and showcased in the catch crop management guidelines.
- Autumn and winter-sown cereal catch crops can successfully establish under field conditions and reduce the risk of N leaching in Waikato, Canterbury and Southland study sites. Establishment success differed annually and locally due to weather conditions and the previous crop in the rotation.
- The earlier the catch crop is established, the greater the potential to reduce N leaching, regardless of the time of year (even in winter). Positive economic and environmental returns were found in most years across all field trial sites but values depend on inter-annual variability (namely rainfall).
- Key mechanisms by which catch crops reduced the risk of N leaching were plant-N uptake and water use. Nevertheless, other processes may also be important, such as microbial immobilisation from root exudates (carbon source), and reduced soil temperatures, slowing mineralisation and nitrification rates. These require further investigation.
- In simulated urine patches winter-sown catch crops can produce yields of up to 12 t DM/ha at green-chop silage maturity (approximately mid-November) in all regions with potential to increase annual biomass production. In Southland, yields accumulate marginally slower than in the other regions, due to cooler temperatures.
- Catch crops can remove significant amounts of soil mineral N. For example, approximately 40 kg N/ha was measured in above-ground biomass by early September, 140 kg N/ha by mid-October and >200 kg N/ha at green-chop silage maturity in November, on average in Canterbury.
- Most of winter-sown catch crop biomass accumulates during October/November. At this time, most plant N uptake has already occurred and the crop progressively dilutes the N concentration.
- Financial analysis has shown that oat catch crop yields of 6.1–10.9 t DM/ha, in the context of a real farm system, can result in returns of $855–1913/ha for standing feed (assuming $0.25/kg DM).

- Cereal catch crops performed better than ryegrass in terms of yield, N uptake and reduced risk of N leaching in all study regions.
- Cereals such as oats, triticale, ryecorn, wheat and barley can all be used as catch crops if sown early enough, offering a range of end-use opportunities (e.g. grazing, green manure, green-chop silage, whole-crop silage, grain). Barley was shown to be less effective at taking up N than other cereal species when sown in winter, while minimal differences were observed between the other four species. Considering bulk feed/production potential at green-chop, crop quality and environmental performance, oats are the preferred option.
- Root systems are of vital importance, this work has suggested that above-ground biomass accumulation and root metabolic activity is more important than specific root architecture.
- No more than 10 kg N/ha was measured in catch crop roots systems at a given point in time between sowing and green-chop silage maturity (November), indicating that N accounted for in above-ground biomass was the main driver for reducing the risk of N leaching.
- Direct drilling or light pre-drilling cultivation should be targeted methods of establishment to minimise additional N input through mineralisation. However, more intensive cultivation may be necessary after heavy stock trampling and/or pugging.
- Oat catch crops appeared to perform marginally better after a kale crop than a fodder beet crop. Further work is required to better understand the mechanisms behind this effect.
- Winter-sown catch crop growth rates are unlikely to respond to late spring applications of N fertiliser. However, seasonal circumstances may mean that crops require some N in spring; crop and/or soil assessments are advised before application.

Publications

Chakwizira, E., Dellow, S. J. and Teixeira, E. I. "Quantifying canopy formation processes in fodder beet (Beta vulgaris subsp. vulgaris var. alba L.) crops". *European Journal of Agronomy* 74 (2016): 144-154. https://doi.org/10.1016/j.eja.2015.12.003.

Chakwizira, E., de Ruiter, J. M., Maley, S. and Teixeira, E. "Evaluating the critical nitrogen dilution curve for storage root crops". *Field Crops Research* 199 (2016): 21-30. https://doi.org/10.1016/j.fcr.2016.09.012.

Chakwizira, E., Teixeira, E., Meenken, E., Michel, A. J. and Maley, S. "Radiation use efficiency and biomass partitioning to storage roots in fodder beet crops". *European Journal of Agronomy* 92 (2018): 63-71. https://doi.org/10.1016/j.eja.2017.10.002.

Khaembah, E. N. and Nelson, W. R. "Transplanting as a means to enhance crop security of fodder beet". *bioRxiv* 3 (2016, 31 May): 056408. https://doi.org/10.1101/056408.

Khaembah, E. N., Teixeira, E. I., Brown, H. E., Chakwizira, E., Maley, S., George, M., Dellow, S., Meenken, E. and de Ruiter, J. "Effect of sowing date on yield of fodder beet and economic returns of a pasture-fodder beet crop sequence". Proceedings of the 2016 Australasian Dairy Science Symposium, Sydney, Australia (2016, 16-18 November). https://www.researchgate.net/publication/339887233_Sowing_date_effects_on_dry_matter_yield_fodder_beet_crops

Khaembah, E. N., Brown, H., Zyskowski, R., Chakwizira, E, de Ruiter, J. and Teixeira, E. I. "Development of a fodder beet potential yield model in APSIM next generation (ApsimX)". *Agricultural Systems* 158 (2017): 23-38. http://www.sciencedirect.com/science/article/pii/S0308521X17301701.

Khaembah, E. N., Teixeira, E. I., Zyskowski, R. and Chakwizira, E. "Luxury nitrogen consumption by fodder beet crops". *Proceedings of the 2018 European Society of Agronomy Conference*, Geneva, Switzerland (2018, 29 August): Abstract#PS-2.1-02. https://www.researchgate.net/publication/327571675_Luxury_Nitrogen_Consumption_by_Fodder_Beet_Crops

Khaembah, E. N., Maley, S., George, M., Chakwizira, E., De Ruiter, J., Zyskowski, R., and Teixeira, E. “Crop growth and development dynamics of two fodder beet (*Beta vulgaris* L.) cultivars sown on different dates in New Zealand”. *New Zealand Journal of Agricultural Research* (2019), pp. 1-18. https://doi.org/10.1080/00288233.2019.1692042.

Malcolm, B., Teixeira, E., Johnstone, P., Maley, S., de Ruiter, J. and Chakwizira, E. "Catch crops after winter grazing for production and environmental benefits”. *Agronomy New Zealand* 46 (2016): 99-108. https://www.agronomysociety.org.nz/files/2016_10._Catch_crops_after_winter_grazing.pdf.

Malcolm, B., Teixeira, E., Johnstone, P., Maley, S,, de Ruiter, J. and Chakwizira, E. “Establishment methods of oat catch crops after winter forage grazing”. *Agronomy New Zealand* 47 (2017): 65-77. https://www.agronomysociety.org.nz/files/2017_8._Est_methods_of_oat_catch_crops.pdf.

Teixeira, E. I., Johnstone, P., Chakwizira, E., de Ruiter, J., Malcolm, B., Shaw, N., Zyskowski, R., Khaembah, E., Sharp, J., Meenken, E., Fraser, P., Thomas, S., Brown, H. and Curtin, D. “Sources of variability in the effectiveness of winter cover crops for mitigating N leaching”. *Agriculture, Ecosystems & Environment* 220 (2015): 226-235. https://doi.org/10.1016/j.agee.2016.01.019.

Teixeira, E. I., Johnstone, P., Chakwizira, E., de Ruiter, J., Malcolm, B., Shaw, N., Zyskowski, R. F., Khaembah, E., Sharp, J., Meenken, E., Fraser, P., Thomas, S., Brown, H. and Curtin, D. “Quantifying key sources of variability in cover crop reduction of N leaching”. In: Weber, T., McPhee, M. J. and Anderssen, R. S. (eds) *MODSIM2015, 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand*, (2015, December): 490–496. ISBN: 978-0-9872143-5-5. www.mssanz.org.au/modsim2015/B4/walmsley.pdf

Zyskowski, R. F., Teixeira, E. I., Malcolm, B. J., Johnstone, P. R. and De Ruiter, J. M. “Effectiveness of winter cover crops to reduce nitrogen leaching losses in cropping systems in Waikato, New Zealand”. *Agronomy New Zealand* 46 (2016): 109-119. https://www.agronomysociety.org.nz/uploads/94803/files/2016_11._Winter_cover_crops_to_reduce_N_leaching.pdf

Teixeira, E., Ausseil, A-G, Cichota, R., Ewert, F., Guo, J., Johnstone, P., George, M., Kersebaum, K. C., Liu, J., Malcom, B., Khaembah, E., Meiyalaghan, M., Zyskowski, R., Michel, A. and Tait, A. “The effectiveness of catch crops to reduce nitrogen leaching losses under climate change”. (2019, in preparation).

Break-crop management systems that sustain high crop production and mitigate soil compaction and N losses

This work was supported with co-funding from the Strategic Science Investment Fund (SSIF) of Plant & Food Research.

Small plot crop production trials were conducted in Canterbury to identify the potential of establishing forage crops using no-tillage to reduce N leaching losses from urinary N following livestock grazing, and fertiliser N inputs needed to sustain high levels of arable and forage crop production in a mixed-cropping rotation. Relationships were defined between soil structural condition (including soil compaction), drainage and N leaching following simulated grazing.

No-tillage forage crop establishment was tested in a grazing trial conducted in Canterbury to quantify its effect on production of the grazed crop and the following catch crop, and its ability to better match the release of N from livestock excreta with crop demand to improve the N use efficiency of the cropping rotation.

Key results of the work undertaken

- Trial results showed that an autumn sown mix of forage oats and Italian ryegrass produced more winter feed and reduced risk of N losses following simulated grazing (treading plus urine N inputs) in winter compared to forage rape.
- Regrowth of Italian ryegrass following winter grazing of forage oat/Italian ryegrass mixes resulted in more rapid uptake of urine-derived N, reducing the risk of subsequent N losses compared to where Italian ryegrass was sown after grazing of crops like forage rape or oats.
- The risk of nitrate leaching is generally greater for grass-to-crop-to-grass renewal systems than for grass-to-grass renewal systems.
- Stock treading during winter grazing of autumn sown forage crops increases soil compaction and nitrous oxide emissions but reduces the risk of nitrate leaching. Performance of subsequent crops is reduced.
- The risks of soil compaction and nitrous oxide emissions following winter grazing of forage crops are greater in heavier (higher clay content), poorly draining soils than in light, free-draining soils, and when the soil water content at the time of grazing is at or above field capacity.
- Increasing amount of recent soil cultivation increased the risk of nitrous oxide emissions when subsequently grazing under wet conditions.
- Compared to conventional cultivation, direct drilling in autumn of forage crops (oats, Italian ryegrass and forage rape) reduced soil compaction from winter grazing and risk of urine N run-off and nitrous oxide emissions.
- Direct drilling was also used successfully to produce high yielding crops of fodder beet and kale for winter grazing. Fodder beet is more sensitive to seed bed preparation than kale and this can lead to more variable beet size and spacing and some yield penalty in direct drilled crops compared to cultivated crops. However, the dry matter yield of kale crops established with no-till was better than that from conventionally tilled crops.
- There is some evidence that winter grazing of fodder beet results in greater soil physical damage than the grazing of kale under the same environmental conditions, due to greater treading pressure with more feed on offer with fodder beet. However, no-till establishment of fodder beet and kale reduced soil compaction from winter grazing and improved the establishment and yield of subsequent cereal crops (e.g. catch crops).
- Overall, combining no-till forage crop establishment with controlled grazing and early establishment of catch crops provides the best option to reduce the risk of soil compaction and N losses from winter grazing. No-till crops can be established at a lower cost of production than with cultivation, making no-tillage forage cropping an economically viable option for producing supplementary feed, while reducing the overall environmental footprint of winter grazing.

Publications

Cichota, C., Vogeler, I., Trolove, S., Malcolm, B., Thomas, S. and Beare, M. H. "Describing the effect of grazing on nitrogen leaching in winter forage-ryegrass rotations". In: *Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2016). http://flrc.massey.ac.nz/workshops/16/Manuscripts/Paper_Cichota_1_2016.pdf.

Hu, W., Tabley, F., Beare, M. H., Tregurtha, C., Gillespie, R., Qiu, W. and Gosden, P. "Short term dynamics of soil physical properties as affected by compaction and tillage in a silt loam soil". *Vadose Zone Journal* 17 (2018): 180115. doi:10.2136/vzj2018.06.0115. https://dl.sciencesocieties.org/publications/vzj/abstracts/17/1/180115.

Hu, W., Beare, M., Tregurtha, C., Gillespie, R,. Lehto, K., Tregurtha, R., Gosden, P., Glasson, S., Dellow, S., George, M., Tabley, F., Qiu, W., Baird, D. "Effects of tillage, compaction and nitrogen inputs on crop production and nitrogen losses following simulated forage crop grazing". *Agriculture, Ecosystems and Environment* 289 (2020) 106733, pp. 1-11. https://doi.org/10.1016/j.agee.2019.106733.

Thomas, S. M., Fraser, P. M., Hu, W., Clough, T. J., van der Klei, G., Wilson, S., Tregurtha R. and Baird, D. "Tillage, compaction and wetting effects on NO_3, N_2O and N_2 losses". *Soil Research* 57 (2019): 670-688. https://doi.org/10.1071/SR18261.

Trolove, S., Thomas, S., Clemens, G. and Beare, M. "The effect of winter forage crop and establishment method on N losses during dairy pasture renewal". In: *Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2016). http://www.massey.ac.nz/~flrc/workshops/16/Manuscripts/Paper_Trolove_2016.pdf.

Trolove, S., Thomas, S., van der Klei, G., Beare, M., Cichota, R. and Meenken, E. "Nitrate leaching losses during pasture renewal – Effects of treading, urine, forages and tillage". *Science of the Total Environment* 651.Pt2 (2019): 1819–1829. https://doi.org/10.1016/j.scitotenv.2018.09.333.

Closed loop nutrient management systems for optimising the use of effluent and manures

Effluent and manure characteristics (e.g. proportion of available to organic N, C:N ratios, and other biochemical constituents) were identified to that reflect the amount and rate of N released from these amendments following application to soil. These relationships were used to develop algorithms that were then validated in soil assays for a selection of manure types and soil types.

Effluent use guidelines were developed in collaboration with end-users.

Key results of the work undertaken

- Measurable effluent characteristics were identified that could be used to predict effluent N supply patterns over 6 months when added to soil.
- Assays were conducted to measure the amount and timing of N supply from dairy effluents applied to different soil types. This dataset was used to test APSIM's representation of effluents and improvements were suggested.
- Scaling results from the assays using APSIM, common analytical measures were identified, as well as relationships suitable for estimating field-scale N supply from slurry and solid effluents applied to cropping soils.
- New industry guidelines <Link to be added once published online> were published which detail key research findings including N supply predictors for effluent applied to cropping soils. Knowledge was transferred to the three major New Zealand analytical laboratories for inclusion in their effluent testing programmes.

Publications

Dexter, M., Ghani, A., Johnstone, P., Houlbrooke, D., Norris, M., Sharp, J. and Longhurst, B. "Lab assessment of N mineralisation from dairy slurry and manures". In: *Moving farm systems to improved attenuation. Currie L. D., Burkitt, L. L. (Eds). Occasional Report No. 28. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2015). http://www.massey.ac.nz/~flrc/workshops/15/Manuscripts/Paper_Dexter_2015.pdf.

Dexter, M., Norris, M., Johnstone, P., Selbie, D., Houlbrooke, D., Sharp, J. and Hedderley, D. "Quantifying the supply of plant available nitrogen from dairy effluents using a laboratory assay approach". *Proceedings* *of the New Zealand Society of Soil Science & Soil Science Australia Joint Conference*, Queenstown (2016, 12-16 December). https://www.researchgate.net/publication/318969957_Quantifying_the_supply_of_plant_available_nitrogen_from_dairy_effluents_using_a_laboratory_assay_approach.

Johnstone, P., Norris, M., Houlbrooke, D., Ghani, A., Sharp, J., Dexter, M. and Wallace, D. "Closed loop nutrient management systems – optimising the use of effluent and manures on cropping farms". *New Zealand Society of Soil Science Conference*, Hamilton (2014, 1-4 December). https://www.researchgate.net/publication/304784114_Closed_loop_nutrient_management_systems_-_optimising_the_use_of_effluent_and_manures_on_cropping_farms

Johnstone, P., Norris, M., Houlbrooke, D., Dexter, M., Sharp, J., Selbie, D. and Hedderley, D. "Quantifying the supply of plant-available nitrogen from dairy effluents to grow crops". *Proceedings of the 2016 International Nitrogen Initiative Conference*, Melbourne, Australia (2016, 4-8 December). https://www.researchgate.net/publication/318970131_Quantifying_the_supply_of_plant-available_nitrogen_from_dairy_effluents_to_grow_crops.

Norris, M., Johnstone, P. R., Wallace, D. F., Arnold, N. P. and Parker, M. "Soil nitrogen supply from effluent-amended pasture soils for forage maize production. *New Zealand Journal of Agricultural Research* (2019), pp. 1-15. https://doi.org/10.1080/00288233.2019.1692876.

Norris, M., Johnstone, P., Dexter, M., Selbie, D., Houlbrooke, D., Sharp, J. and Hedderley, D. "Predicting nitrogen supply from dairy effluent applied to two New Zealand soils". *New Zealand Journal of Agricultural Science* 62.4 (2019): 438-456. https://doi.org/10.1080/00288233.2018.1508478.

Sharp, J., Johnstone, P., Norris, M., Houlbrooke, D., Selbie, D., Dexter, M. and Hedderley, D. "Predicting the supply of plant-available nitrogen from dairy effluents using APSIM". *Proceedings of the New Zealand Society of Soil Science & Soil Science Australia Joint Conference*, Queenstown (2016, 12-16 December). https://www.researchgate.net/publication/317886909_Predicting_the_supply_of_plant-available_nitrogen_from_dairy_effluents_using_APSIM

Farm systems for improved N use efficiency and reduced nitrate leaching losses

Farm system models were improved using data from FRNL experiments and used to assess the impact of new technologies for improving N use efficiency and reducing nitrate leaching. This way component research results were translated to farm level, increasing the value of the research.

A co-development approach was used to link research with farmers, Māori agribusiness enterprises and rural professionals. This ensured the FRNL research was result-oriented and addressed practical questions.

A network of monitor farmers (arable, dairy, mixed livestock and mixed arable-dairy) was established to monitor their farm system and management, and adoption of alternative pasture and cropping practices. This helped to evaluate adoptability and risks of proposed system changes, nutrient balances and nitrate leaching losses (using Overseer) and to determine requirements for knowledge development, communication and decision support. The participating monitor farmers were crucial in providing critical feedback and testing and demonstrating the researched options on farm at scale. Research questions and experiments were adjusted accordingly. This flexibility in the programme proved to be a critical factor for its success.

Farm system modelling to evaluate effects of alternative pasture species and forage crops on production, profitability and environmental impact of livestock and arable farms

Programme objectives were discussed with the participating monitor farmers to ensure system measurements and modelling output aligned with their expectations. Assumptions in models were discussed in the science team to focus model development.

A major APSIM model improvement involved a methodology for simulating climate-driven growth and N uptake by diverse pastures on different soil types. This development reflected the diverse functional characteristics of the root structure of a diverse pasture as affected by the species mix. Development in Overseer allowed entering of monthly crude protein (CP) data representing the differences in seasonal CP of standard and diverse pastures.

The platform for the arable sector consisted of data flows between Simple Crop Resource Uptake Model (SCRUM) operating within APSIM, and the online farm records and management software, ProductionWise. Model development included crops that have been added in SCRUM e.g. plantain, tall fescue, oil seed rape and linseed. A script was written to facilitate re-growth for crops that were cut at various stages during the season before being harvested for seed.

The platform for dairy consisted of data flows between three models, the DairyNZ Whole Farm Model (WFM), Urine Patch Framework (UPF), and APSIM. The UPF was developed to enable modelling of varying urine patch N loads, frequency and size. Other major improvements included developing capabilities in WFM regarding diverse pastures, pasture persistency, crop rotations, and cropping costs. The need to approximate the drainage characteristics of the monitor farms necessitated the expansion of the soils library for both WFM and APSIM with ten dairy-dominant soils with varying drainage characteristics. Feed qualities were derived from the crop and pasture quality database described earlier. The MOLLY and MINDY animal models in WFM were compared with the metabolism stall trials to ensure an acceptable N partitioning.

For the mixed-livestock farms, Farmax® Pro and Overseer models were used for farm system level assessment of integrating diverse pasture (including plantain) and/or forage crops.

Practical and best options for implementing the most promising mitigation options (plantain in pasture, fodder beet and catch crops) were identified in workshops with arable, dairy and mixed livestock farmers and researchers. These were tested in scenario modelling studies for productivity, profitability and mitigation of nitrate leaching. Risks of potential pollution swapping, or other unintended consequences, were identified. The farm system modelling supported the implementation of the mitigation options on the monitor farms.

Decision and management support resources were developed for successful implementation of FRNL mitigation options on commercial farms. FRNL collaborates with Overseer to enable the model to reflect the benefits of plantain in pasture, fodder beet and catch crops.

KEY RESULTS OF THE WORK UNDERTAKEN

- Modelling a hypothetical sheep & beef farm found that having a diverse pasture on 50% of the farm area without changing the stocking policy of the farm, increased farm profit by 16%, due to the sale of surplus pasture as conserved forage. The total farm N leaching values obtained from APSIM, based on excretal N amounts from Overseer, showed that the use of diverse pastures on the 50% flat area of the farm decreased N leaching in an average year by 35%. The reduction in N leaching estimated from Overseer was only 6%, which is due to the lower N concentration of the diverse pasture.
- For the arable sector some paddocks of the two monitor farms with high N leaching were modelled to include a combination of winter cover crop, reduced N fertiliser rate (where modelled soil profile indicated mineral N amounts in excess of the crop requirements), and reduced irrigation. Results showed that with improved management N leaching can be reduced by 20-30% with increases in gross margin from cost reductions and selling the cover crop of $490 to $778/ha.
- Five dairy monitor farms were modelled in WFM-UPF-APSIM to compare their current systems (baseline) with alternative scenarios. The three common system changes for the alternative scenarios were, 1) reduced N fertiliser, reduced cow numbers, reduced supplement imported, 2) fodder beet crop used as a transition crop on the platform and combined with kale as a winter crop on the support block, 3) a block of diverse pastures established on the platform. The general trend was an improvement in profitability for the alternative scenarios compared with baseline. Modelling suggested N leaching reduction of 9-21% for three farms, but no reduction in two others. Sense-checking showed that farmers were generally in agreement with the model trends, and some were already implementing aspects of the alternative scenarios in the second year of the programme.
- Model output suggested that the economic incentives associated with the use of diverse pastures were too weak on their own to motivate wide-scale adoption under standard conditions (e.g. no N limits). Reductions in N leaching from dairy farms were found to add substantially to the value proposition offered by alternative pasture species.
- Reductions in N leaching of about 40% were predicted when all the pasture area on a dairy farm was sown to diverse pasture mixtures, compared with standard mixtures. The reduction in N leaching was mainly derived from a reduction in the concentration of N present in urine, and to a much lesser extent by a reduction in the total amount of urinary N excreted by cows.
- Diverse pastures appeared to be a cost-effective way to reduce N leaching. However, there is a need to understand and improve the persistence of diverse pastures to reduce the cost of re-establishing species, mainly forbs.
- Overall, the modelling results suggested that the benefit of sowing diverse pasture mixes (relative to the standard ryegrass-clover mix) will be greatest on soils with low water holding capacity and in climates experiencing extended dry periods during the main growing season.
- A scenario study for an FRNL monitor farm tested the effects of mitigation actions the farmer was going to implement: expanding the effluent area, growing fodder beet on the milking platform, replacing some pasture with maize silage, growing diverse pastures on 7% of the milking platform, and including a feed pad. The cumulative effect of these changes was an increase of 3 and 13% in production and profit respectively, but only a 5% decrease in N leaching as estimated for the combined platform and support

block areas over 3 climate years. A hypothetical scenario, of a third of the platform in diverse pastures, less N fertiliser, all fodder beet grown on the milking platform, lifted and fed on the feed pad, and with an oats catch crop following fodder beet, increased production and profit by 2 and 10%, respectively, with a reduction in N leaching of 19%.

- A scenario for the dairy and beef integrated FRNL monitor farm in North Canterbury on a light soil, implementing mixed species pasture, fodder beet and catch crops, reduced leaching by 19%. Average profitability was similar than if the farm was converted to dairy only, but with less variability between years due to variable weather and prices for milk and meat.
- Modelling the farm system effects of pastures with 50% plantain on 28% of the pastoral area of another monitor farm, a high input Canterbury dairy farm on a free-draining soil, showed a reduction in leaching by 5%. This was the greatest reduction achieved by only substituting part of the standard pastures by mixed pastures containing plantain. While the diuresis effect of plantain reduced the N load in a urine patch, it also led to a larger area of the paddock covered by urine and a greater area covered by overlapping urine patches. Also, imported supplements negated some of the benefits of plantain.
- Another modelling exercise demonstrated that greater reductions can be achieved when, in association with the diuresis effect of plantain, N fertiliser rate is reduced and a longer round length is adopted, which increases the C:N ratio of pasture. This scenario reduced pasture harvested by 8% for Canterbury and 16% for Waikato, and reduced N leaching by 31% for Canterbury and 59% for Waikato. This compared to reductions of 6% and 21% for the Canterbury and Waikato scenarios, respectively, for the diuresis effect only.
- The farm system modelling indicated that high-performing farms have scope to reduce N leaching by 20% and still increase profit by implementing some of the FRNL mitigation options.

PUBLICATIONS

Beukes, P., Edwards, P. and Coltman, T. “Modelling options to increase milk production while reducing N leaching for an irrigated dairy farm in Canterbury”. *Journal of New Zealand Grasslands* 79 (2017): 147-152. https://www.grassland.org.nz/publications/nzgrassland_publication_2859.pdf.

Beukes P. C., Chikazhe, T. and Edwards, J. P. “Exploring options to reduce N leaching while maintaining profitability within a Canterbury farm business comprising several distinct enterprises”. *New Zealand Journal of Grasslands* 80 (2018): 191-194. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/324.

Khaembah, E. N. and Horrocks, A. “A modelling approach to assessment and improvement of nitrogen management on New Zealand arable farms: a case study”. *Agronomy New Zealand* 48 (2018): 1-11. www.agronomysociety.org.nz/files/ASNZ_2018_01._Modelling_N_management.pdf.

Romera, A. J., Doole, G. J., Beukes, P. C., Mason, N. and Mudge, P. L. "The role and value of diverse sward mixtures in dairy farm systems of New Zealand: An exploratory assessment”. *Agricultural Systems* 152 (2017): 18-26. https://doi.org/10.1016/j.agsy.2016.12.004.

Vibart, R. E., Vogeler, I., Dodd, M. and Koolaard, J. "Simple versus Diverse Temperate Pastures: Aspects of Soil–Plant–Animal Interrelationships Central to Nitrogen Leaching Losses”. *Agronomy Journal* 108.6 (2016): 2174-2188. DOI: 10.2134/agronj2016.04.0193. https://dl.sciencesocieties.org/publications/aj/abstracts/108/6/2174.

Vogeler, I., Vibart, R. and Cichota, R. "Potential benefits of diverse pasture swards for sheep and beef farming”. *Agricultural Systems* 154 (2017): 78-89. https://doi.org/10.1016/j.agsy.2017.03.015.

Co-development for practice change to reduce nitrate leaching

The monitor farmers collected an extensive amount of data on farm management, some daily, others monthly or annually. Farm performance was summarised annually.

Key results of the work undertaken

- The farmers tested and demonstrated the mitigation options on farm. The use of plantain, fodder beet and catch crops did not appear to impact negatively on feed supply and farm profit.
- Annual modelling of the farm systems and management showed year-to-year variation in nitrate leaching, and for some farms substantial improvements in the course of the programme.
- The potential benefits of plantain in pasture, fodder beet and catch crops were not reflected in Overseer (used for the pastoral farms) as yet, but any effects on efficiency of the use of purchased N (N fertiliser, N in supplementary feeds) or purchased N surplus would be noticed. FRNL and Overseer collaborate to ensure these FRNL options will be modelled in the near future.
- Low-N forage crops and catch crops did not cover a large proportion of any farm and therefore by themselves did not substantially reduce N leaching of the whole farm. The same was true for substituting high-N pasture or supplements for low-N supplements.
- For most farms, a suite of mitigation actions was necessary to achieve N leaching reductions of 20%. Some of the FRNL monitor farms achieved larger reductions.

Monitor farms' performance – sheep and beef

- The sheep and beef farms had low average leaching across the farm (<30kg N/ha/year) and reducing that average was very difficult. <update with 2018/19 results>
- The year-to-year variation of N leaching amounted to 18 and 22% for the sheep and beef farms (the difference between the lowest and highest N leaching estimated). The key driver was weather conditions determining the number of stock the farms were able to carry, and meat produced. <update with 2018/19 results>
- The greatest source of leaching from sheep and beef farms was modelled from paddocks of forage crop used for winter grazing of adult cows or adult bulls for beef (70 to 106 kg N/ha/year, depending on soil type). <update with 2018/19 results>
- Soil maps proved a good tool for the sheep and beef farms to assist in choosing heavy soils for establishing winter crops to reduce leaching rates and hold N for a subsequent catch crop. However, potential impact on greenhouse gas emissions will need to be taken into account to avoid pollution swapping.

Monitor farms' performance – dairy

- Key drivers of N leaching on the dairy farms were the annual application rate of N fertiliser and the amount of supplementary feed brought onto the farm. Changes in N leaching were strongly correlated with changes in N surplus.
- The dairy farms started introducing plantain in pasture, grew fodder beet on the milking platform for autumn feed and started using catch crops after autumn or winter grazed fodder crop. Three of the farms improved their surplus of purchased N and N Conversion Efficiency (NCE) and reduced their Overseer-estimated N leaching. Note that Overseer does not take the effects of plantain, fodder beet and catch crops into account as yet, but N surplus will reflect better NCE and less N at risk of leaching.
- Year-to-year variation amounted to differences of 17-108% within a dairy farm for surplus of purchased N and 15-55% for N leaching. Response to autumn weather conditions appeared to have a relatively large impact. When weather was favourable and more N fertiliser was applied to utilise growth conditions, or when weather was unfavourable and more supplementary feed was used to maintain milk production, N surplus and Overseer's estimated N leaching increased.
- Practical options for integrating diverse pastures and crops to reduce nitrate leaching were tested on two Māori-owned monitor farms. The challenges associated with their use in a high rainfall environment were identified.

- Profitable options for reducing nitrate leaching were determined by modelling six Māori agribusiness enterprises (a mix of dairy and sheep and beef), including the use of plantain, fodder beet and oats.
- Practical outcomes from the entire programme were extended to the wider Māori agribusiness community. For smaller groups, this was found to be most effective through field days, consultation and huis, whereas the broader community was reached through media, conferences, publications, reports, email and wider industry networks.

Monitor farms' performance – arable

- For the arable farms the key drivers of N leaching were drainage and soil type. The amount of soil mineral N at risk of leaching was mainly determined by N fertiliser rate. Other factors were mineralisation of N-rich crop residues and the duration of fallow periods.
- Two management strategies that helped reduce the amount of soil N available for leaching were (1) calculating fertiliser N requirements with a recommendation system that accounts for soil mineralisation; and (2) sowing catch crops immediately after the summer harvest to mop up residual soil N or N mineralised from soil organic matter and crop residues.
- Better accounting for plant N requirements and available soil N reduced the surplus of purchased N of the arable farms: from -3 in the first year to -30 to -69 in the years thereafter (Wakanui), from -10 to -22 to -82 (Mayfield), and from -20 to -16 to -120 (St Andrews).
- Leaching on the arable farms was estimated with APSIM, which included actual rainfall and drainage (not the long-term averages as in Overseer). Leaching dropped from 34 kg N/ha to 10-20 kg N/ha thereafter for Wakanui and from 20 to 8-18 kg N/ha for Mayfield, and it increased from 0 to 7 kg N/ha for St Andrews (drainage on St Anders was 0 to 117mm in this period).

Publications

Burggraaf, V. T., Rennie, G. M., Edwards, P. and Pinxterhuis, I. "Meeting nitrogen discharge allowances on a Rotorua dairy farm – a case study". In: *Nutrient loss mitigations for compliance in agriculture. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 32. Fertilizer and Lime Research Centre*, Massey University, Palmerston North, New Zealand (2019). http://flrc.massey.ac.nz/workshops/19/Manuscripts/Paper_Burggraaf_2019.pdf.

Burggraaf, V. T., Rennie, G. M., Edwards, P. and Pinxterhuis, I. "BRIEF COMMUNICATION: A case study of the effects of diet and winter management on dairy production, profit and nitrate leaching in Rotorua". *Journal of the New Zealand Society of Animal Production* 79 (2019): 71-73. http://www.nzsap.org/system/files/proceedings/brief-communication-case-study-effects-diet-and-winter-management-dairy-production-profit-and.pdf.

Dalley, D., Dynes, R., Pinxterhuis, I., Chapman, D., Tait, N. and Monaghan, R. "Can Nutrient Limits and Greenhouse Gas Reductions Be Achieved While Operating Profitable Farm Systems". *Proceedings of the South Island Dairy Event*, Dunedin (2018, 25-26 June): 39-55. https://side.org.nz/wp-content/uploads/2018/07/side-proceedings-2018-web.pdf.

Edwards, G., Beare, M., Pinxterhuis, I. and Edwards, P. "Forages for reduced nitrate leaching". *Proceedings of the South Island Dairy Event Conference,* Lincoln University, Lincoln (2015). https://side.org.nz/wp-content/uploads/2015/10/2.7-Forages-for-reduced-nitrate-leaching.pdf

Edwards, P., Pinxterhuis, I. B. and Bewsell, D. "Forages for Reduced Nitrate Leaching - a cross-sector approach". *Proceedings of the 5th International Symposium for Farming Systems Design*, Montpellier, France (2015, 7-10 September): 293-294. http://www.fagro.edu.uy/fsd/agro2015/documents/proceedings.pdf.

Edwards, J. P. and Pinxterhuis, J. B. "Identifying research priorities for establishing plantain on-farm. *Proceedings of the Australasian Dairy Science Symposium*, Palmerston North (2018, 21-23 November): 203-207.

http://wired.ivvy.com/event/DairyS/image/display/account/34583/file/10250382/j/fc7830bf6f9003a4f816a87b4a96cffd.

Knook, J., Dynes, R., Pinxterhuis, I., de Klein, C. A. M., Eory, V., Brander, M. and Moran, D. "Policy and practice certainty for effective uptake of diffuse pollution practices in a light-touch regulated country". *Environmental Management* (2020). https://doi.org/10.1007/s00267-019-01242-y.

Pinxterhuis, J. B., Beare, M. H., Edwards, G. R., Collins, R. P., Dillon, P. and Oenema, J. "Eco-efficient pasture based dairy farm systems: a comparison of New Zealand, The Netherlands and Ireland". *Grasslands Science in Europe* 20 (2015): 349-366. https://www.cabdirect.org/cabdirect/abstract/20153417813.

Pinxterhuis, I., Coltman, T., Edwards, P. and Parker, L. "Achieving the required N leaching reductions on dairy farms in the Selwyn Area, Canterbury – A real-life example". *South Island Dairy Event*, Lincoln (2017, 28 June): 68-79. https://side.org.nz/wp-content/uploads/2017/06/2.3-Achieving-the-required-N-leaching-reductions-Ina-Pinxterhius.pdf.

Pinxterhuis, I. B. and Edwards, J. P. "Comparing nitrogen management on dairy farms - Canterbury case studies". *Journal of New Zealand Grasslands* 80 (2018): 201-206. https://www.nzgajournal.org.nz/index.php/JoNZG/article/view/329.