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Refining estimates of nitrogen leaching for the New Zealand agricultural greenhouse gas inventory

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Contents

1. Executive Summary 1
2. Background 5
3. Methods 6
   - 3.1 Review of literature for grazed pastures and cropping systems 6
   - 3.2 Examine estimates of N leaching calculated using OVERSEER 6
   - 3.2.1 Dairy farm systems 7
   - 3.2.2 Sheep and beef systems 7
   - 3.2.3 Cropping systems 8
4. Results and Discussion 11
   - 4.1 Literature review of measured nitrogen leaching from grazed pastures and cropping systems 11
   - 4.1.1 Relationship between measured and modelled nitrogen leaching 11
   - 4.1.2 Estimates of $Frac_{LEACH}$ values for measured grazing and cropping nitrogen leaching studies 12
   - 4.2 Estimates of nitrogen leaching loss from NZ agricultural systems 15
   - 4.2.1 Dairy farm systems 15
   - 4.2.2 Sheep and Beef farm systems 20
   - 4.2.3 Cropping systems 24
   - 4.2.4 Comparison with estimates from Environment Aotearoa (2019) 26
5. Conclusions and Recommendations 27
5. Further Research 29
6. Acknowledgements 30
7. References 30
8. Appendices 33
   - 8.1 Literature review of New Zealand trials measuring nitrogen leaching from grazed pastures 33
   - 8.1.1 Dairy cow nitrogen leaching studies 33
   - 8.1.2 Sheep and beef nitrogen leaching studies 38
   - 8.2 Literature review of New Zealand trials measuring nitrogen leaching from arable and vegetable cropping systems 43

1. Executive Summary

This report reviews the suitability of the $Frac_{LEACH}$ parameter used to estimate the proportion of nitrogen (N) applied to agricultural land that is lost via leaching and runoff of N. The New Zealand (NZ) agricultural greenhouse gas (GHG) inventory methodology currently employs a uniform $Frac_{LEACH}$ value of 0.07 of key N inputs, which is used for estimating a proportion of the indirect nitrous oxide (N_2O) emissions from agriculture. The $Frac_{LEACH}$ value is based on a limited number of input parameters and is calculated using the following formula:

$$Frac_{LEACH} = (Leached\ N)/ (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM})$$

where Leached N is the measured or modelled annual quantity of N leached from the agricultural system (kg N/year). F_{SN} is the amount of N applied in synthetic nitrogen fertiliser (kg N/year), F_{ON} is the amount of N applied in the non-manure component of organic fertilisers (kg N/year), F_{PRP} is the amount of N applied in manure deposited by grazing livestock in pasture, range and paddock (kg N/year), F_{CR} is the amount of N contributed by decomposition of crop residues left on fields (kg N/year), F_{SOM} is the nitrogen mineralisation from loss of soil organic matter in mineral soils through land management for cropland remaining cropland (kg N/year). The current $Frac_{LEACH}$ value does not include F_{CR} or F_{SOM} in its application.

The research in this report comprised of firstly reviewing published literature on N leaching from grazed pastures (dairy and sheep and beef farms) and cropping (arable and vegetable) systems. Secondly, modelling was undertaken to examine estimates of N leaching calculated using the OVERSEER® nutrient budget model (hereafter referred to as OVERSEER) for a range of NZ agricultural systems and farm system types, which were compared with data on the specific N inputs for each agricultural system. A large amount of survey data was used to ensure the range of farm systems types was representative of NZ agricultural systems. This allowed an evaluation of the links between estimated N leaching and the key N input parameters in the NZ GHG inventory (e.g. N fertiliser, urine and dung N). The main findings of the research were:

Relationship between measured and modelled nitrogen leaching loss

- Measured N leaching losses from paddock-scale grazing systems and cropping studies were compared with leaching values modelled by OVERSEER. There was a positive linear correlation (R^2=0.56) between measured and modelled N leaching losses from paddock-scale grazing systems studies. Similarly, there was a strong linear correlation (R^2 =0.73) between measured and modelled N leaching losses for cropping systems based on the OVERSEER crop module using a limited dataset.

Dairy farm systems

- The $Frac_{LEACH}$ value for measured N leaching data based on paddock-scale dairy grazing systems studies (conducted mainly on research farms in Waikato, Manawatū and Southland) had an average value of 0.067 (ranged from 0.02 to 0.16) of excreta N + fertiliser N.

- Regression analyses revealed that the combination of excreta N + fertiliser N input parameters was the best predictor for N leaching loss for dairy farm systems relative to using individual excreta-N or fertiliser-N input parameters.
- DairyBase survey data of up to 460 individual dairy farms were processed to obtain regional averages across multiple years and modelled using OVERSEER. Results showed a slight increase in the average value (weighted for regional milk production) for $Frac_{LEACH}$ (i.e. leached-N/[excreta N + fertiliser-N]) over time. The earliest period assessed (2004-05) had an average value of 0.073, which increases to 0.079, 0.079 and 0.080 for 2009-2010, 2014-2015 and 2017-18 years, respectively.
- The $Frac_{LEACH}$ value was also estimated for case-study dairy farms across four NZ catchments (Bog Burn in Southland, Toenepi in Waikato, Waikakahi in Otago and Waiokura in Taranaki; 2009 and 2017) with the average $Frac_{LEACH}$ value in the range of 0.07-0.09 (individual farms ranged from 0.05 to 0.11).

Sheep and beef farm systems

- The $Frac_{LEACH}$ value for measured N leaching data based on five paddock-scale sheep and beef grazing systems had an average $Frac_{LEACH}$ (i.e. leached-N/[excreta-N + fertiliser-N]) value of 0.07.
- As for dairy systems, excreta N + fertiliser N input parameter was the best predictor for N leaching loss for sheep and beef farm systems, although there was little effect of fertiliser-N due to low fertiliser rates used in these systems.
- Estimates of excreta-N were based on OVERSEER diet N concentration values (e.g. 3.1-3.6% N) instead of the average diet N concentration (3.0% N) used in the NZ GHG Inventory methodology.
- Beef+LambNZ survey data (from over 400 farms) for the seven main farm classes across NZ were modelled using OVERSEER. The $Frac_{LEACH}$ value for the sheep and beef farm systems had a national average (weighted for relative animal production) of 0.081 (ranging from 0.05 to 0.11).
- Analyses of 60 individual sheep and beef farm systems from across NZ regions showed an average $Frac_{LEACH}$ value of 0.085, ranging from 0.04 to 0.17.

Arable and vegetable cropping systems

- The studies with measured N leaching data for arable and vegetable cropping systems had an average $Frac_{LEACH}$ value based on leached-N/fertiliser-N of 0.26.
- Short-term measurements of N leaching during periods of individual crop growth showed large variability and therefore estimates were used for calculating $Frac_{LEACH}$ based on whole-year cropping systems and fertiliser N and crop residue N inputs.
- Crop residue N is an important source of N, which is currently accounted for in the NZ GHG inventory and should be included in estimating $Frac_{LEACH}$ for cropping systems.
- The national average value (weighted for relative areas of crops across the main regions) of $Frac_{LEACH}$ (i.e. Leached-N/[fertiliser-N + residue-N]) was 0.10 for arable and vegetable cropping systems based on fertiliser N input, calculated crop

residue-N and OVERSEER-predicted whole-season leaching. There was some variability in $Frac_{LEACH}$ between regions with values of 0.15, 0.07, 0.09 and 0.16 for Auckland, Hawke's Bay, Canterbury and Southland, respectively.

Conclusions and Recommendations

The analysis indicated that the most effective data inputs (i.e. with the highest level of correlation) for grazed pastoral farming systems to use for calculating N leaching and $Frac_{LEACH}$ was the sum of N inputs from animal excreta and fertiliser-N rather than using excreta and fertiliser-N inputs alone. The national GHG inventory methodology currently uses these same inputs. The calculation of $Frac_{LEACH}$ for cropping systems should be based on whole-year cropping systems with fertiliser N and crop residue N inputs. Thus, the following equations are recommended for calculating $Frac_{LEACH}$ for grazed pastures (dairy and sheep and beef) and cropping systems (arable/vegetable):

$$\textit{Grazed pastoral systems } Frac_{LEACH} = (\text{Leached N})/(F_{SN} + F_{ON} + F_{PRP})$$

$$\textit{Cropping systems } Frac_{LEACH} = (\text{Leached N})/(F_{SN} + F_{ON} + F_{PRP} + F_{CR})$$

where Leached N is the measured or modelled annual quantity of N leached from the agricultural system (kg N/year), F_{SN} *is the amount of N applied in synthetic nitrogen fertiliser (kg N/year),* F_{ON} *is the amount of N applied in the non-manure component of organic fertilisers (kg N/year),* F_{PRP} *is the amount of N applied in manure deposited by grazing livestock in pasture, range and paddock (kg N/year),* F_{CR} *is the amount of N contributed by decomposition of crop residues left on fields (kg N/year).*

This analysis indicated some differences between land-use activities in NZ-weighted average $Frac_{LEACH}$ values. Based on the NZ GHG inventory methodology currently employing a uniform $Frac_{LEACH}$ value of 0.07 for dairy, sheep & beef, and arable/vegetable cropping systems, this study proposes the following three options could be considered in refining the $Frac_{LEACH}$ value, which are briefly outlined below:

1. **$Frac_{LEACH}$ based on measured N leaching data.** Based on limited grazing studies with measured N leaching loss data the $Frac_{LEACH}$ value could be 0.07 for grazing systems (dairy and sheep and beef systems) and 0.26 for arable/vegetable cropping systems. We would advise caution on using $Frac_{LEACH}$ values based on a limited number of studies in confined catchments for national GHG calculations.
2. **$Frac_{LEACH}$ based on land-use activity.** The $Frac_{LEACH}$ values could be separated by land-use activity and this would result in $Frac_{LEACH}$ values of 0.08 for dairying, 0.08 for sheep and beef and, 0.10 for arable/vegetable cropping systems. While the $Frac_{LEACH}$ values are the same for dairy and sheep and beef systems, issues relating to separating the fertiliser N inputs between these two systems is likely to be difficult to currently implement for national GHG calculations.
3. **Single $Frac_{LEACH}$ value for grazing (i.e. covering both dairy and sheep and beef, as well as others such as deer and goats) and separate value for arable and vegetable cropping systems**. A single $Frac_{LEACH}$ value for grazing (dairy and sheep and beef; 0.08) and a separate value for cropping systems (0.10) could

be considered. This option would negate issues about separation of fertiliser N inputs between dairy and sheep and beef farm systems for national GHG calculations.

In summary, our primary recommendation is to use a single $Frac_{LEACH}$ value of 0.08 for grazing systems (covering both dairy and sheep and beef systems, as well as could be considered for others such as deer and goats) and a separate $Frac_{LEACH}$ value of 0.10 for arable and vegetable cropping systems (Option 3).

It is important to recognise that the $Frac_{LEACH}$ value for cropping systems should be interpreted with caution because of uncertainties associated with predicted leaching values by OVERSEER. It is also recognised that there is some spatial variability associated with site factors such as soil and rainfall/drainage, farm system intensity and crop rotations and management. However, it is unrealistic to recommend a complex modelling system for estimating N leaching since only a limited range of input data is available for use within the national GHG inventory. The above recommended values were based on nationally weighted average values that accounted for regional variations in farms and animal or crop production across NZ. Furthermore, they also showed little variation over time during the last decade (based on analyses over three-time intervals) within the dairy and sheep and beef farm systems, indicating reasonable stability in these average $Frac_{LEACH}$ values.

2. Background

In New Zealand (NZ), agricultural soils are a major source of nitrous oxide (N_2O) emissions, which is well recognised to be an important contributor to national greenhouse gas (GHG) emissions (MfE, 2019). In 2017, agriculture accounted for almost half of the NZ gross GHG emissions with indirect N_2O emissions from leaching and runoff estimated to be 0.5 Mt CO_2-e, accounting for 1.3% of NZ's GHG agricultural emissions (MfE, 2019).

Indirect N_2O emissions from leached nitrogen (N) is estimated using the $Frac_{LEACH}$ parameter in the NZ agricultural GHG Inventory based on the Intergovernmental Panel for Climate Change (IPCC) methodology. The $Frac_{LEACH}$ parameter accounts for the proportion of N applied to agricultural land that is lost through leaching and run-off into local water bodies (e.g. groundwater, wetlands, rivers). A proportion of leached N is subsequently emitted as N_2O. Currently, a uniform $Frac_{LEACH}$ value of 0.07 is used for all N applied to agricultural soil throughout NZ (Thomas et al., 2005). The $Frac_{LEACH}$ value is based on a limited number of input parameters and is calculated using the following formula:

$$Frac_{LEACH} = (Leached\ N)/ (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM})$$

Where Leached N is the measured or modelled annual quantity of N leached from the agricultural system (kg N/year), F_{SN} *is the amount of N applied in synthetic nitrogen fertiliser (kg N/year),* F_{ON} *is the amount of N applied in the non-manure component of organic fertilisers (kg N/year),* F_{PRP} *is the amount of N applied in manure deposited by grazing livestock in pasture, range and paddock (kg N/year),* F_{CR} *is the amount of N contributed by decomposition of crop residues left on fields (kg N/year),* F_{SOM} *is the nitrogen mineralisation from loss of soil organic matter in mineral soils through land management for cropland remaining cropland (kg N/year).* The current $Frac_{LEACH}$ value does not include F_{CR} or F_{SOM} in its application.

In grazed pastures in NZ, the main source of N leaching is from animal excreta deposited during grazing, with urine being the major contributor (e.g. Ledgard et al., 2009; Monaghan et al., 2016). The use of N fertiliser leads to increased recycling of N in excreta via N-boosted pasture with more N leaching from this indirect source, as well as potential for direct leaching of fertiliser-N (e.g. Ledgard et al., 1999). In cropping systems, important sources of N leaching are fertiliser-N and N mineralised from crop residues and soil organic N (Thomas et al., 2012; Fraser et al., 2013). It is important to recognise that since the study and recommendation by Thomas et al. (2005), the IPCC guidelines were revised (IPCC 2006) and adopted by NZ. One of the key changes was inclusion of N inputs from crop residues and from soil organic matter mineralisation, these two inputs were excluded in the original IPCC methodology (van der Weerden et al. 2011), and the calculations used by Thomas et al. (2005).

The primary aim of this research was to review the $Frac_{LEACH}$ parameter currently used in NZ agricultural GHG inventory to assess if it is still appropriate for modern NZ agricultural systems. More specifically, the research aimed to provide recommendations on modifying (if necessary) the current $Frac_{LEACH}$ value of 0.07 of key N inputs using either a single weighted average value or a set of disaggregated values based on activity, livestock type and/or region. This was achieved by reviewing published literature on N leaching from NZ grazed pastures (dairy and sheep and beef) and cropping (arable and vegetable) systems. Analysis of datasets using the OVERSEER® nutrient budgets model (hereafter called OVERSEER) was then used to examine estimates of N leaching calculated for a range of

NZ agricultural systems and to compare these with data on the specific N inputs used in the NZ GHG Inventory (e.g. N fertiliser, urine and dung N).

3. Methods

3.1 Review of literature for grazed pastures and cropping systems

Published literature on N leaching from grazed pastures (dairy, sheep and beef) and cropping (arable and vegetable) systems were reviewed to extend the previous research by Thomas et al. (2002, 2005). The review focused on NZ data and where available, the review collated N leaching data from the NZ studies and linked it to data on specific agricultural N inputs across the studies that are identified in the IPCC 2006 guidelines and NZ GHG Inventory (e.g. N fertiliser, urine and dung N). Data from the NZ paddock-scale grazing system studies were also analysed using OVERSEER (Science version 6.3.3) to determine the correlation between measured and modelled N leaching.

3.2 Examine estimates of N leaching calculated using OVERSEER

Estimates of N leaching were calculated using OVERSEER (Science version 6.3.3) for a range of NZ agricultural systems (dairy, sheep and beef, and cropping) and these were compared with data on the specific N inputs (noted in section 3.1) for each agricultural system. This analysis used representative real farm type and regional data over time that reflects actual farm practices and inputs. Results were then used to assess predictions of N leaching using the specific inputs as well as to the current default value of 0.07 of total N inputs. Data sources included DairyNZ DairyBase, Beef+LambNZ Economic Service, StatsNZ and individual farm data. Where applicable, estimates of N leaching loss from OVERSEER were compared with examples from the Environment Aotearoa (2019) report tool (which are based on simple averages per animal with regional soil/climate data). More specific details of the modelling approach for each farm system are outlined below.

For each pastoral farm system studied, data on calculated excreta N (in urine and dung) was obtained from the OVERSEER model. In addition, per-hectare data on animal dry matter intake from OVERSEER was obtained and multiplied by the assumed averaged diet N concentrations from the NZ GHG Inventory model (i.e. 3.7% N for dairy farms and 3.0% N for sheep and beef farms). The resulting calculated N intake by animals had the N output in product (i.e. milk, meat, wool) subtracted to estimate the excreted-N, so that it aligned more closely to that estimated using the NZ GHG Inventory methodology. The estimate of excreta-N from OVERSEER accounts for different N concentrations in brought-in feeds and in pasture according to seasonality and effects of inputs such as N fertiliser. Thus, it was possible to test for effects of differences in excreta-N estimated by OVERSEER and by the NZ GHG Inventory methodology.

3.2.1 Dairy farm systems

3.2.1.1 Survey (DairyBase) data of regional average dairy farms

Survey data from dairy farms across NZ has been collated in the DairyNZ DairyBase dataset. The data used in this project represented a summary of regional average results for analysis using OVERSEER and covers:

- *Regions*: Northland, Waikato, Bay of Plenty, Taranaki, Lower North Island, Westland, Marlborough/Canterbury and Otago/Southland
- *Years*: 2004/05, 2009/10, 2014/15 and 2017/18
- *Farm system intensity*: Data for 2018/19 covering low, medium and high brought-in feed inputs for the Waikato region
- *Soils*: Representative soils were identified for each region. Additionally, a range of soils were analysed for the Waikato region
- *Rainfall*: Long-term average regional rainfall data was used in the analyses. In addition, a sensitivity analysis was carried out on the effects of variation in annual rainfall in the Waikato region.

In all cases, data on farm animal numbers, productivity, animal dry matter intake and N fertiliser inputs was recorded.

3.2.1.2 Dairy farm catchment data

Dairy farms in four NZ catchments (Bog Burn in Southland, Toenepi in Waikato, Waikakahi in Otago and Waiokura in Taranaki) were selected and analysed using OVERSEER. These catchments were part of a research study examining farm practices and environmental emissions, including changes in emissions over time (Wilcock et al., 2013). Data were collected from 4, 7, 4 and 6 case study farms in the Bog Burn, Toenepi, Waikakahi and Waiokura catchments, respectively, for 2009 and 2017. Data from an additional 5 farms for the Waiokura catchment in 2017 were also collected and used in the analysis.

Farm data was analysed using OVERSEER for estimated annual N leaching. Farm data on animal numbers, productivity, animal dry matter intake and N fertiliser inputs was also recorded.

3.2.2 Sheep and beef systems

3.2.2.1 Survey sheep and beef farm class data

Sheep and beef farm class data from Beef+LambNZ Economic Service was collated for analysis using OVERSEER and covers:

- *Farm classes:* High country, hard hill country, hill country and finishing farm systems covering North and South Islands
- *Years*: 2004/05, 2009/10, 2014/15 and 2017/18

- *Soils*: Representative soils were identified for each farm class. Additionally, a range of soils were analysed for farm class 4 (North Island hill country), which was selected for this sensitivity analysis because it produces the largest amount of sheep and beef products across all farm classes.
- *Rainfall*: Average rainfall data was used in the analyses for each farm class. In addition, a sensitivity analysis was carried out on the effects of variation in annual rainfall for farm class 4.

Farm data was analysed using OVERSEER for estimated annual N leaching. Farm data on animal numbers, productivity, animal dry matter intake and N fertiliser inputs were also recorded.

3.2.2.2 Individual sheep and beef farms

Estimates of N leaching were calculated using OVERSEER for 60 individual (anonymized) sheep and beef farms from across NZ. Farm site data (e.g. annual rainfall, soil, land slope) was recorded, as well as data on animal numbers, productivity, animal dry matter intake and N fertiliser inputs. This dataset was used to understand the effects of variation in system productivity and input data on calculated N leaching relative to N inputs.

3.2.3 Cropping systems

Arable and vegetable crop rotations consist of multiple crops grown over several years with variable timing and amounts of N inputs (e.g. fertiliser and residue) and outputs (e.g. plant uptake and N leaching) affected by the type of crop and its management. Crop residues left after harvest will mineralise and add to the leachable mineralised N pool in the following crop, and in some cases will continue to add to the mineralised pool in the crop following that. Hence, modelling rotations over several years provides more representative estimates of the N inputs and losses for arable and vegetable cropping.

Estimates of N leaching from representative cropping sequences were calculated using OVERSEER and covers:

- *Cropping rotations:* Nineteen sequences with representative arable and vegetable crops
- *Regions:* Auckland, Hawke's Bay, Canterbury, Southland.
- *Soils*: Representative cropping soils were identified for each region.
- *Rainfall*: Average rainfall data was used in the analyses for each region.

Representative vegetable and arable cropping rotations were developed with up to 5 crops from the four main growing New Zealand regions (Table 1). These cropping sequences were selected based on expert input with the sequences being developed as follows: Firstly, crops accounting for >6% of the national tonnage or acreage were selected (StatsNZ 2018). The crops were then categorised based on North and South Island production. Finally, production was ranked by region/district within each Island. In creating sequences, less economically important crops e.g. green oats in Auckland (Pukekohe) were considered necessary break crops.

Crop management comprised of seed crops (clover and ryegrass) and forage crops (annual ryegrass and forage oats) which were managed under the cut and carry regime, so no nitrogen was returned as manure or urine. Nitrogen fertiliser was applied as calcium ammonium nitrate (incorporated) at sowing and coated urea was used for top-dressing. Fertiliser application followed the recommendations of Reid and Morton (2019) for vegetables and the Foundation for Arable Research (FAR Arable Extra No. 16 & 36) for cereals.

OVERSEER models crop rotations over a two-year period (shown as "Year 1" and "Reporting year" in Table 1). The model outputs the summary of inputs and outputs for the Reporting year only. "Year 1" is effectively used to initialise model for the "Reporting year". Therefore, to simulate a 5-year rotation in OVERSEER, it was necessary to build the rotation using five two-year periods (Table 1). To produce the crop rotation sequence, the "Reporting year" becoming Year 1 in successive rotations (Table 1). Using the user-defined function available in OVERSEER (Science version 6.3.3), Rotations 2–5 were re-initialised using plant N, soil N and residue N (i.e. carry-over N conditions) from the previous season. For Rotation 1, default OVERSEER initial conditions based on the following paddock history were assumed.

- Auckland: years in pasture = 0; prior land use = fallow,
- Hawke's Bay: years in pasture = 0; prior land use = crop,
- Canterbury: years in pasture = 0; prior land use = crop,
- Southland: years in pasture = 2; prior land use = crop.

The inventory uses the same approach to estimate above and below-ground crop residue nitrogen inputs as OVERSEER (Thomas et al., 2012). In brief, the above-ground crop residue is calculated as the proportion of the total above ground dry biomass (shoot). The below-ground residue is estimated from the root to shoot ratio. Nitrogen contents of the residues are determined from residue N concentrations. Thomas et al. (2012) recommended using the same factors used in OVERSEER for the inventory calculations. Residue inputs estimated by OVERSEER and calculated following the Inventory methodology (MfE, 2019) were assessed.

Mineralisation of soil organic matter (SOM) is also included in the NZ inventory calculation of $Frac_{LEACH}$. In practice this is only accounted for through changes in land use at the national scale, for example the change in land area of perennial crops to annual crops or vice versa, otherwise it is assumed that SOM is at an equilibrium or steady state and mineralisation of this SOM does not contribute N for leaching. The activity information is described in the LULUCF chapter of the NZ inventory. It is assumed through the IPCC approach that there is no change in SOM after 20 years of change in land use. In reality, mineralisation of SOM occurs in cropping rotations and it is questionable whether, on average, SOM in cropping land in NZ has reached an equilibrium. To be consistent with the NZ Inventory steady state approach, we have calculated $Frac_{LEACH}$ as the proportion of N leached from the inputs of fertiliser and crop residues only, i.e. without specifically accounting for any change in SOM. We have also included OVERSEER estimates of N mineralisation of SOM in our results and provide this as a non-steady state comparison. In each of our cropping scenarios, OVERSEER predicted SOM mineralisation would contribute to the estimate of N leached. To provide an overall value for $Frac_{LEACH}$ for cropping we have weighted the values using the areas cropped in NZ based on national statistics (StatsNZ 2018).

TABLE 1: Arable and vegetable crops in rotations for four New Zealand regions (Auckland, Hawke's Bay, Canterbury and Southland) used for modelling.

Auckland	**Year 1**												**Reporting year**											
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Rotation 1	Oats (manure)			Potatoes						Oats (manure)			Onions											
Rotation 2	Onions												Potatoes							Oats (manure)				
Rotation 3		Potatoes								Oats (manure)			Lettuce			Spinach			Cabbage				Lettuc
Rotation 4	Lettuce			Spinach			Cabbage				Lettuce					Potatoes				Oats (manure)			
Rotation 5					Potatoes			Oats (manure)					Broccoli				Pumpkin					Oats	

Hawkes Bay	**Year 1**												**Reporting year**											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Rotation 1		Squash						Italian ryegrass					Peas	Sweet corn						Forage oats				
Rotation 2	Peas	Sweet corn						Forage oats					Tomatoes							Italian ryegrass				
Rotation 3	Tomatoes							Italian RG (cut & carry)					Beetroots							Italian ryegrass		Onions		
Rotation 4	Beet roots							Italian RG	Onions											Italian ryegrass				

Canterbury	**Year 1**												**Reporting year**											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Rotation 1	Ryegrass seed			Seed		Silage							Peas (dried)							Broccoli				
Rotation 2	Peas (dried)							Broccoli					Carrots											
Rotation 3	Brocc	Carrots											Grain oats						Clover seed					

Canterbury 2	**Year 1**												**Reporting year**											
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Rotation 4	Autumn wheat												Autumn wheat											
Rotation 5	Autumn wheat													Oats (manure)			Barley							

Southland	**Year 1**												**Reporting year**											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Rotation 1		Potatoes							Oats (manure)				Carrots (1st crop)											
Rotation 2	Carrots (1st crop)												Carrots (2nd crop)											
Rotation 3	Carrots (2nd crop)												Peas							Wheat				
Rotation 4	Peas								Wheat											Forage oats				
Rotation 5	Wheat							Forage oats						Potatoes						Ryegrass pasture				

4. Results and Discussion

4.1 Literature review of measured nitrogen leaching from grazed pastures and cropping systems

The review of published literature on N leaching from grazed pastures (dairy and sheep and beef) and cropping (arable and vegetable) systems is outlined in the appendices (Section 8.0).

Published and unpublished data from a range of field trials across NZ over the past three decades, covering dairy farming (14 trials) and sheep and/or beef farming (5 trials) systems where N leaching was measured, have been summarised. It must be noted that most trials were on research farms in Waikato, Manawatū and Southland, which provided the ability to carry out detailed measurements, but they may not be highly representative of commercial farms. Most trials included comparison of two or more different treatments or management practices. Measured N leaching in dairy farm systems varied between 6 and 105 kg N/ha/yr, while for the sheep and/or beef farm systems it ranged from 4 to 43 kg N/ha/yr. The grazing system studies selected for this review will be different to a wider research dataset that includes paddock, small-plot and lysimeter studies not used in this review but that would be used for comprehensive validation of the OVERSEER model, which was not the purpose of this project.

The cropping review compiled a list of references and summarised the amounts of N applied and leached under a range of different NZ vegetable and arable crops. Most of these data are from controlled experiments comparing different treatments that are not representative of the range of practices on commercial cropping farms. The measured or estimated amounts of N leached varied considerably: 6 to 292 kg N/ha for vegetable crops and 1 to 142 kg N/ha for arable crops.

4.1.1 Relationship between measured and modelled nitrogen leaching

There was a positive linear correlation (R^2=0.56) between measured and modelled N leaching loss from NZ paddock-scale grazing systems studies (Figure 1). The slope of the fitted line was slightly less than 1:1, but it is evident from the data that there is variability about the line. The relationship was also influenced by a single high value data point where measured N leaching was 105 kg N/ha/yr. It should be noted that each data point is an average of 2-4 years of data and in the case of the latter average value (105 kg N/ha/yr), it varied between 65 and 146 kg N/ha/yr between the three individual years of measurement. Excluding this single high value data point had no significant effect on the slope of the fitted line between measured and modelled N leaching loss from NZ paddock-scale grazing systems studies. Thus, overall, it can be concluded that the OVERSEER model provided a reasonable prediction of the average N leaching for the range of field trials and treatments studied.

The literature review for cropping systems highlighted that the OVERSEER crop module is not as well tested as the pastoral model. However, the simulation of crop rotations described by Francis et al. (2006 and 2007) in OVERSEER, indicated a good agreement between measured and predicted N leaching (R^2 =0.73). It is important to consider that the Francis et al. (2006 and 2007) experiment comprised of three crops (potatoes, peas

and wheat) and was located at one site. The testing of the OVERSEER crop module is an on-going process following recommendations from reviews (OVERSEER Crop Module Review Report 2016, Dunbier et al., 2013, Williams et al., 2013). Among the areas of interest is that the 60 cm depth at which leaching is generated in the model fails to capture the value of deep-rooted crops resulting in over-estimation of N leaching loss.

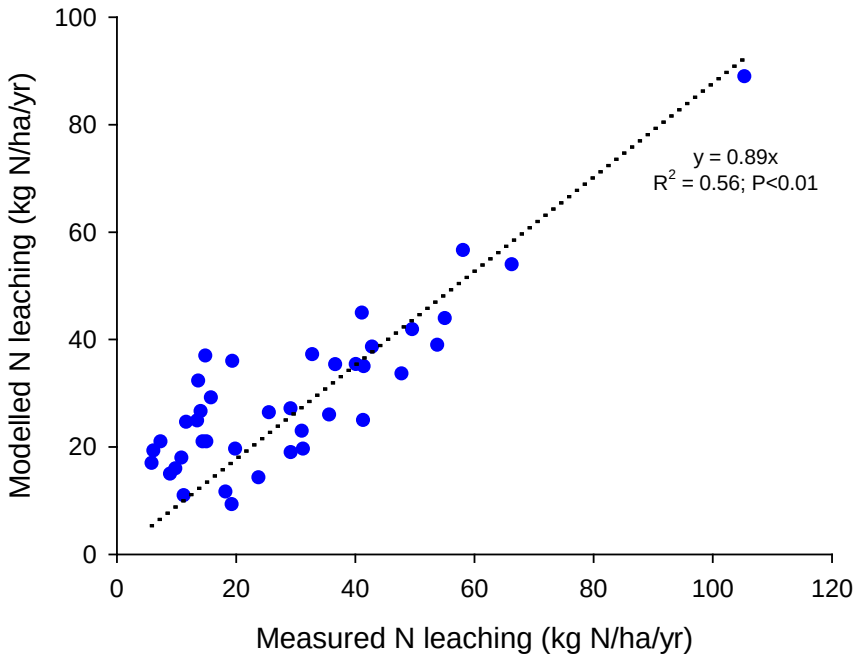


Figure 1: Relationship between measured and modelled annual nitrogen leaching loss (kg/N/ha/year) based on measured data from New Zealand paddock-scale grazing system studies and modelled data using OVERSEER.

4.1.2 Estimates of $Frac_{LEACH}$ values for measured grazing and cropping nitrogen leaching studies

The $Frac_{LEACH}$ value for all farm systems using N leaching measurements from paddock-scale grazing systems from the literature review relative to the sum of OVERSEER-based excreta-N and fertiliser N inputs averaged 0.063 (ranged from 0.02 to 0.18). Based on Inventory-based excreta-N and fertiliser N inputs the $Frac_{LEACH}$ value was similar at 0.067 (ranged from 0.02 to 0.16). The corresponding value for the dairy system studies was 0.064 (range 0.02 to 0.16).

The $Frac_{LEACH}$ value for N leaching studies of sheep and beef systems was slightly higher than dairy at 0.073 (range 0.02-0.13) using excreta and fertiliser N inputs based on a limited number of leaching studies.

The average $Frac_{LEACH}$ value for measured N leaching from arable and vegetable cropping studies was 3-fold higher than grazed pasture systems at 0.26 based on fertiliser N inputs alone. Most of the N leached from arable crops is derived either from the net N mineralisation of soil organic N (including recent residues) or from N fertiliser applied to the previous crop that remained in the soil following harvest (Thomas et al., 2005). However, in most of these studies, these key inputs of non-fertiliser sources (i.e. crop residues and mineralised SOM) are not measured or reported, despite their large contribution to soil mineral N pool that can be leached or utilised by the plant.

4.1.2.1 Correlation between measured N leaching and N input parameters

The correlation between measured N leaching and the N input parameters was examined for various N input parameters for the grazing system studies. The best fit was obtained with the sum of excreta-N plus fertiliser-N, which is the source of N inputs used in the current Inventory methodology for estimating $Frac_{LEACH}$ (Figure 2). The R^2 value for measured N leaching versus OVERSEER-based excreta-N plus fertiliser-N was 0.47 (Figure 2). It was lower for OVERSEER-based excreta-N only at 0.42 or fertiliser-N only at 0.30 (Figure 2). Similar relationships were found using Inventory-based excreta-N input values (data not presented). There was no additional benefit from including brought-in feed-N in the estimation and the correlation coefficient with feed-N only was 0.06 (not significant; data not presented).

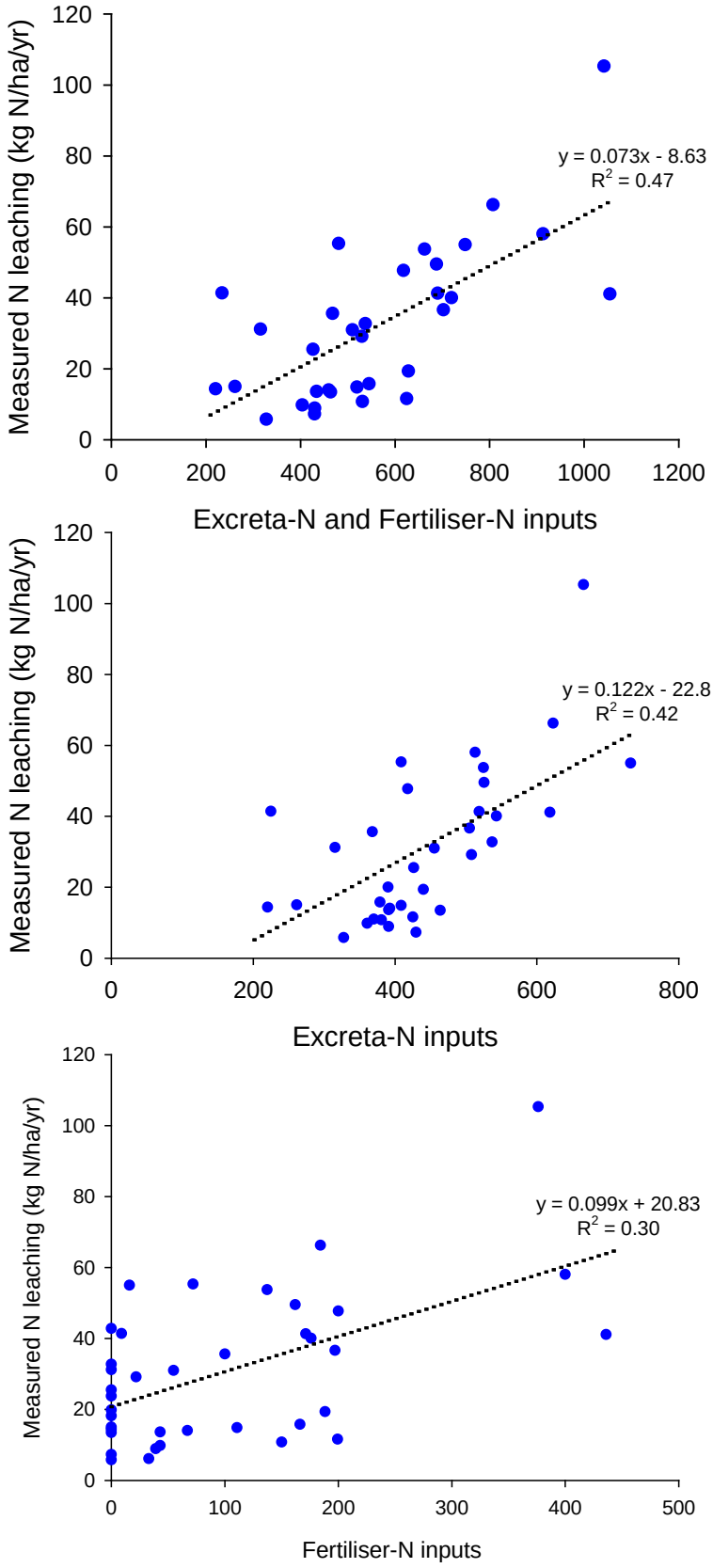


Figure 2: Relationship between measured N leaching (kg/N/ha/year) in grazing system studies and OVERSEER-based excreta-N and/or fertiliser-N input parameters.

4.2 Estimates of nitrogen leaching loss from NZ agricultural systems

4.2.1 Dairy farm systems

4.2.1.1 Survey (DairyBase) dairy farm data

The dataset of surveyed farms for the average farm systems across all regions of NZ in the DairyNZ DairyBase represents the most comprehensive and detailed dairy farm system dataset available. Depending on the year of data collection it was based on a national survey total of up to 460 farms per year (Ledgard et al., 2020).

Details of average data from the farm systems across the regions over time is given in Table 2, while a summary of $Frac_{LEACH}$ is given in Table 3. There were regional differences in farm system intensity and productivity, as evident from stocking rates of 2.2 to 3.5 cows/ha in Northland and Canterbury+Marlborough, respectively. This coincided with the amounts of N excreted per hectare varying from approximately 280 to 630 kg N/ha/yr, respectively. The N leaching was variable across regions, ranging from approximately 30 to 90 kg N/ha/yr. The latter was located in Westland region and the high N leaching loss was influenced by the effects of high rainfall and associated drainage on increasing N leaching loss.

The $Frac_{LEACH}$ (i.e., leached-N/[OVERSEER-based excreta-N + fertiliser-N]) was least in Waikato and Otago+Southland at approximately 0.06. In the low farming-intensity Northland region the $Frac_{LEACH}$ was around 0.12, while it was approximately 0.08 in Canterbury+Marlborough and up to 0.15 in Westland (Table 2).

Overall correlation analyses showed similar effects associated with different N input parameters to that in section 4.1.2.1 with the correlation coefficient being highest for excreta-N + fertiliser-N and no benefit from including brought-in feed-N (data not presented).

The NZ weighted average $Frac_{LEACH}$ value based on regional pattern of milk production was 0.080 in 2017/18 and had increased over time from 0.073 in the 2004/05 season using OVERSEER-based excreta-N and fertiliser-N inputs (Table 3). This was associated with a small increase over time (particularly between 2004/05 and 2009/10) in most input and output parameters in all regions. Similar NZ weighted average $Frac_{LEACH}$ values were calculated using the Inventory-based excreta-N and fertiliser-N inputs (Table 3). Interestingly, differences over time were smaller when the N in brought-in feeds was included in the $Frac_{LEACH}$ value (Table 3). However, these effects were minor, and the use of brought-in feeds and their associated N content is not included in the NZ GHG Inventory methodology.

Table 2: Summary of average dairy farm data for different regions across New Zealand over time in the stocking rate, relative milk production, N inputs, N outputs and $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from OVERSEER-based excreta and fertiliser N). Data were derived from DairyNZ DairyBase.

Region	Year	Cows/ha	Fertiliser N	Brought-in feed N	Product N	OVERSEER-based excreta N	Leached N	Leached-N / (excreta+fert N)	% NZ milksolids[!]
Bay of Plenty	2004-05	2.74	126	13	68	386	44	**0.09**	10.2%
	2009-10	2.75	110	27	63	368	47	**0.10**	8.8%
	2014-15	2.77	99	34	76	400	47	**0.09**	9.2%
	2017-18	2.79	111	44	74	391	46	**0.09**	8.8%
Lower North Island	2004-05	2.71	91	27	66	384	30	**0.06**	9.8%
	2009-10	2.76	124	19	70	375	29	**0.06**	9.5%
	2014-15	2.77	94	32	77	414	35	**0.07**	8.9%
	2017-18	2.74	112	32	71	402	33	**0.06**	8.3%
Canterbury+Marlborough	2004-05	3.05	170	32	85	515	58	**0.08**	14.4%
	2009-10	3.30	182	25	93	584	66	**0.08**	19.8%
	2014-15	3.45	206	43	105	634	73	**0.08**	22.8%
	2017-18	3.42	207	45	101	608	71	**0.09**	24.3%
Northland	2004-05	2.20	83	8	46	277	38	**0.11**	7.1%
	2009-10	2.26	92	27	47	280	44	**0.12**	5.6%
	2014-15	2.27	99	30	54	285	44	**0.11**	5.6%
	2017-18	2.27	99	30	55	288	50	**0.13**	5.1%
Otago+Southland	2004-05	2.69	104	31	73	435	34	**0.06**	11.2%
	2009-10	2.71	106	20	75	444	35	**0.06**	15.2%
	2014-15	2.78	138	33	77	452	38	**0.06**	14.8%
	2017-18	2.65	148	35	77	443	37	**0.06**	16.5%
Taranaki	2004-05	2.82	85	13	63	388	38	**0.08**	12.4%
	2009-10	2.82	117	19	67	384	40	**0.08**	11.0%
	2014-15	2.85	134	44	80	428	43	**0.08**	10.5%
	2017-18	2.80	132	53	71	395	44	**0.08**	9.8%

Table 2 continued.

Region	Year	Cows/ha	Fertiliser N	Brought-in feed N	Product N	OVERSEER-based excreta N	Leached N	Leached-N / (excreta+fert N)	% NZ milksolids[1]
Waikato	2004-05	2.90	117	11	69	390	27	**0.05**	30.4%
	2009-10	2.91	99	35	67	363	30	**0.07**	25.8%
	2014-15	2.93	99	52	79	380	30	**0.06**	25.4%
	2017-18	2.91	118	47	77	382	33	**0.07**	23.5%
Westland	2004-05	2.63	105	10	51	354	61	**0.13**	4.5%
	2009-10	2.77	149	9	53	371	75	**0.14**	4.3%
	2014-15	2.78	206	20	58	374	94	**0.16**	2.8%
	2017-18	2.82	136	31	55	366	79	**0.16**	3.8%

[1] from dairy statistics (LIC/DairyNZ, 2019)

Table 3: Estimates of $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from excreta calculated using GHG Inventory methodology or OVERSEER, and from fertiliser and brought-in feed) for an NZ-average dairy farm system over time. Data were obtained from DairyNZ DairyBase farm survey data for regions across NZ and a weighted average calculated according to total regional milksolids production.

Year	Leached N/ (Inventory-based excreta-N + fertiliser-N)	Leached N/ (OVERSEER-based excreta-N + fertiliser-N)	Leached N/(OVERSEER-based excreta-N + fertiliser-N +brought-in feed-N)
2004/05	0.072	0.073	0.071
2009/10	0.079	0.079	0.075
2014/15	0.079	0.079	0.074
2017/18	0.080 (0.06-0.17)	0.080 (0.06-0.16)	0.074 (0.06-0.17)

A sensitivity analysis was carried out to examine the effects of differences in soils and rainfall, which are known factors influencing the amounts of N leached. The effects of this for the main Waikato region for the 2017/18 dataset are shown in Table 4. This illustrates the importance of correctly accounting for soils and climate for the farm system analyses. It also highlights the importance of doing an appropriate weighting across regions and farm systems in the process of estimating a weighted NZ average value. For analyses in section 4.2.1.1, selection of soil and climate data were based on use of spatial data using S-map for soils and the NIWA spatial map for rainfall.

Table 4: Sensitivity analysis of the effects of soil (at 1260 mm/yr rainfall) and rainfall (assuming a mix of allophanic and gley soils) on N leaching calculated using OVERSEER for the Waikato 2017/18 average dairy farm system, with no other factors changed.

Soil Order	N leaching (kg N/ha/yr)	Annual rainfall (mm/yr)	N leaching (kg N/ha/yr)
Organic	26	900	17
Podzol, Gley	32	1100	25
Allophanic	35	1300	34
Pumice	36	1500	40
Pallic	43	1700	48

For dairy farm systems, the degree of intensity (i.e. amount of feed per area) is likely to influence the level of N leaching. This is an important consideration when deriving a single national value that is representative of a range of farm systems. Given NZ dairy farm systems can be assigned to low, medium and high feed-input systems, the potential effect of system level on N leaching was examined by analysis of the average datasets from the DairyNZ DairyBase for each of these systems in Waikato for 2017/18 (Table 5). That analysis showed some variation across the average farm systems, being highest in the high feed input system where a relatively high amount of N input occurred in the brought-

in feeds. This illustrates the importance of the analysis of N leaching appropriately accounting for the inputs and productivity of the farm systems. The data summarised in the previous section for the different regions across NZ was based on a relatively large farmer survey that covered the range in farm systems that existed within each of the regions across NZ.

Table 5: Sensitivity analysis of low, medium or high brought-in feed input systems on N leaching calculated using OVERSEER for average Waikato 2017/18 dairy farm systems. Average survey data for farms in the three categories was from DairyNZ DairyBase.

	Low	Medium	High
Fertiliser N (kg N/ha/yr)	121	120	153
Brought-in feed N (kg N/ha/yr)	22	48	179
Product N (milk+meat; kg N/ha/yr)	93	95	147
Leached N (kg N/ha/yr)	31	32	49

4.2.1.2 Dairy farm catchment data

This dataset was based on a research study of four case-study dairy catchments across NZ to understand implications for water quality. A limited number of farms had detailed recorded data for analysis in this study and it showed less variation between catchments or regions and over time than in the national regional study outlined in section 4.2.1.1. In all cases, the average $Frac_{LEACH}$ value was in the range 0.07-0.09 in 2017 (Table 6), with individual farms varying between 0.048 and 0.111. There was little difference in $Frac_{LEACH}$ between 2009 and 2017 years, despite some differences in two catchments that were mainly related to changes in either irrigation practices or farmer representation between years.

While this study involved a limited number of dairy farms in different catchments across NZ, the average $Frac_{LEACH}$ values were similar to those for the average values for the corresponding regions outlined in section 4.2.1.1.

Table 6: Estimates of $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from fertiliser and from excreta calculated using OVERSEER and associated N input data for dairy farm systems in four NZ dairy catchments over time.

	2009			2017		
	Excreta + fertiliser N	Leached N	$Frac_{LEACH}$	Excreta + fertiliser N	Leached N	$Frac_{LEACH}$
Bog Burn	614	49	0.080	664	51	0.076
Toenepi	588	40	0.068	568	38	0.067
Waikakahi	525	32	0.061	702[1]	47[1]	0.067[1]
Waiokura	557	50	0.088	678[2]	57[2]	0.086[2]

[1]Associated with changes in farms and irrigation practices

[2]Associated with increase in number of farms in the catchment analysed

4.2.2 Sheep and Beef farm systems

4.2.2.1 Sheep and beef farm class survey data

The dataset of surveyed farms for the average farm systems across the main sheep and beef farm classes in New Zealand from Beef+LambNZ annual survey data represents the most comprehensive and detailed dataset available. It was based on a national survey with a total of over 400 farms per year.

Details of average data from the farm systems across the farm classes over time are given in Table 7, while a summary of $Frac_{LEACH}$ is given in Table 8. There were differences between farm classes in system intensity and productivity, as evident from stocking rates of 1 to 16 stock units/ha (1 stock unit is equivalent to feed intake of approximately 600 kg dry matter/ha or approximately one ewe plus lamb). Fertiliser N inputs were minimal on farm classes 1-3 and increased up to 22 kg N/ha/yr on finishing farms. There was a large difference in the product N and excreta-N per hectare, varying by over ten-fold. Similarly, the N leaching increased from 2 kg N/ha/yr on South Island high country through to 21 kg N/ha/yr on South Island intensive finishing farms (Table 7).

The $Frac_{LEACH}$ (i.e., leached-N/[excreta-N + fertiliser-N]) was least for the North Island hard hill country at approximately 0.05 and was highest for the least-intensive South Island high and hill country farm classes at 0.11-0.13. These $Frac_{LEACH}$ estimates were derived using OVERSEER to estimate excreta-N. There was a relatively large effect of methodology on estimated values for excreta N, which was evident from the differences in diet N concentration of 3.1-3.6% using OVERSEER compared to the average of 3.0% N used in the NZ GHG Inventory methodology. Table 8 shows that the NZ average $Frac_{LEACH}$ value was higher when estimated using the NZ GHG Inventory methodology. The diet N concentrations used in OVERSEER provide a more accurate estimate of excreta-N inputs rather than Inventory-based excreta-N estimates, and therefore it is more appropriate to employ OVERSEER-based estimates of excreta-N inputs.

Based on the relative effective areas of land used for different farm classes across NZ, the weightings for the farm classes would be 27, 17, 12, 21, 5, 14 and 4% for farm classes 1-7, respectively (data from Beef+LambNZ). These weightings were used to calculate an average N leaching estimate of approximately 10 kg N/ha/yr (Table 8). Similarly, a weighting according to animal productivity was used to calculate a weighted NZ-average $Frac_{LEACH}$ value. This value based on inputs from fertiliser-N and excreta-N calculated using OVERSEER for an NZ-average sheep and beef farm system averaged 0.081 for 2017/18 (Table 8).

Table 7: Summary of average sheep and beef farm data for different farm classes across New Zealand (North Island NI and South Island SI) over time in the stocking rate, diet N concentration (estimated in OVERSEER), N inputs, N outputs and $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from excreta and fertiliser N). All N-related data are in kg N/ha/yr. Data were derived from Beef+LambNZ Economic Service data.

Farm class	Year	Stock units/ha	Sheep:beef ratio	Fertiliser N	Diet %N	Product N	OVERSEER-based excreta N	Leached-N	Leached-N/ (excreta+fertiliser-N)
1.SI high country	2004/05	0.98	3.1	1	3.16	2	17	2	**0.13**
	2009/10	1.02	3.1	1	3.13	2	18	2	**0.13**
	2014/15	1.30	2.9	1	3.13	2	22	3	**0.13**
	2017/18	1.27	2.4	1	3.14	2	20	3	**0.11**
2.SI hill country	2004/05	4.49	2.7	3	3.25	7	78	9	**0.11**
	2009/10	4.19	2.1	3	3.24	7	72	9	**0.12**
	2014/15	4.99	2.1	4	3.25	9	86	10	**0.11**
	2017/18	4.14	2.0	5	3.24	6	71	9	**0.12**
3.NI hard hill country	2004/05	9.50	2.0	12	3.26	14	166	8	**0.04**
	2009/10	8.46	1.7	2	3.25	14	147	8	**0.05**
	2014/15	8.62	1.6	6	3.25	13	150	8	**0.05**
	2017/18	7.09	1.6	7	3.25	12	124	7	**0.06**
4.NI hill country	2004/05	10.83	1.4	14	3.28	19	185	17	**0.09**
	2009/10	9.75	1.3	6	3.28	18	166	16	**0.09**
	2014/15	10.15	1.2	13	3.28	20	173	17	**0.09**
	2017/18	9.76	1.1	12	3.28	21	166	16	**0.09**
5.NI Intensive finishing	2004/05	12.70	0.9	22	3.6	26	239	14	**0.05**
	2009/10	11.09	0.8	12	3.58	22	207	13	**0.06**
	2014/15	11.14	0.9	16	3.61	23	211	13	**0.06**
	2017/18	9.59	0.7	16	3.58	21	179	13	**0.06**
6.SI breeding/finishing	2004/05	9.26	3.9	15	3.3	17	152	9	**0.05**
	2009/10	9.06	2.6	9	3.28	19	148	9	**0.06**
	2014/15	9.31	2.0	22	3.28	22	153	11	**0.06**
	2017/18	8.47	2.1	14	3.28	21	138	10	**0.06**
7.SI Intensive finishing	2004/05	15.69	13.8	10	3.45	234	272	20	**0.07**
	2009/10	14.20	11.0	12	3.40	34	238	21	**0.08**
	2014/15	14.06	10.6	16	3.44	33	242	20	**0.08**
	2017/18	12.55	7.1	17	3.41	29	212	19	**0.08**

Table 8: Estimates of $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from fertiliser-N and excreta-N calculated using GHG Inventory methodology or OVERSEER) for an NZ-average sheep and beef farm system over time. Data were obtained from Beef+LambNZ farm survey data for farm classes across NZ and a weighted average calculated according to relative total animal live-weight sold.

Year	Leached N (kg N/ha/yr)	Leached N/(Inventory-based excreta-N + fertiliser-N)	Leached N/ (OVERSEER-based excreta-N + fertiliser-N)
2004-05	10.4	0.082	0.079
2009-10	10.1	0.091	0.079
2014-15	10.8	0.089	0.078
2017-18	10.2	0.093 (0.06-0.13)	0.081 (0.05-0.11)

4.2.2.2 **Individual sheep and beef farm data**

Data was surveyed from 60 individual sheep and beef farms from across NZ in 2012/2013. One benefit of this dataset was that it used site-specific farm data for each farm, such as for soils, annual rainfall and land-slope data, whereas the farm class data in section 4.2.2.1 required assumptions about these site data for the average farm systems. Table 9 summarises results from these individual farms and gives mean values. The $Frac_{LEACH}$ calculated using the OVERSEER-based estimate of excreta-N was about 10% lower than that calculated using GHG Inventory methodology. This is explained by the higher calculated excreta-N due to the diet N concentration calculated in OVERSEER (range of 3.0 to 3.7%) being higher than the average value of 3.0 %N assumed in the NZ GHG Inventory methodology.

There was a wide range in farm system intensity, which was greater than that for the average farm class results. Consequently, there was a wider range in N leaching (4-35 kg N/ha/yr) and $Frac_{LEACH}$ (0.035-0.165) than those estimated from the averages across the farm classes (Table 9).

An indication of variation in data for leached N relative to excreta+fertiliser N is given in Figure. 3. The correlation coefficient ($R^2 = 0.38$, $P<0.01$) was the same for excreta-N and for excreta+fertiliser N. The single correlation of leached N with fertiliser N was not significant (data not given) and influenced by many farms with little or no added N fertiliser.

The mean $Frac_{LEACH}$ value (i.e. leached-N/[OVERSEER-based excreta-N + fertiliser-N]) of 0.085 for the 60 individual sheep and beef farm data (Table 9) is similar to the mean value for the NZ-weighted average from the farm class survey data of 0.081 (Table 8).

Table 9: Farm and nitrogen (N) data from a study of 60 individual sheep and beef farms from across New Zealand in 2012/2013, including estimates of $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs from fertiliser-N and excreta-N calculated using GHG Inventory methodology or OVERSEER).

	Mean	Minimum	Maximum
Stock units/ha	11.4	0.5	20.3
Sheep:cattle ratio	3.8	0.1	57
Fertiliser N (kg N/ha/yr)	15	0	122
Product N (meat+wool; kg N/ha/yr)	9	1	23
OVERSEER-based excreta-N (kg N/ha/yr)	199	44	341
Inventory-based excreta-N (kg N/ha/yr)	180	40	322
N leaching (kg N/ha/yr)	18	4	35
Leached N/(OVERSEER-based excreta-N + fertiliser-N)	0.085	0.035	0.165
Leached N/(Inventory-based excreta-N + fertiliser-N)	0.095	0.035	0.177

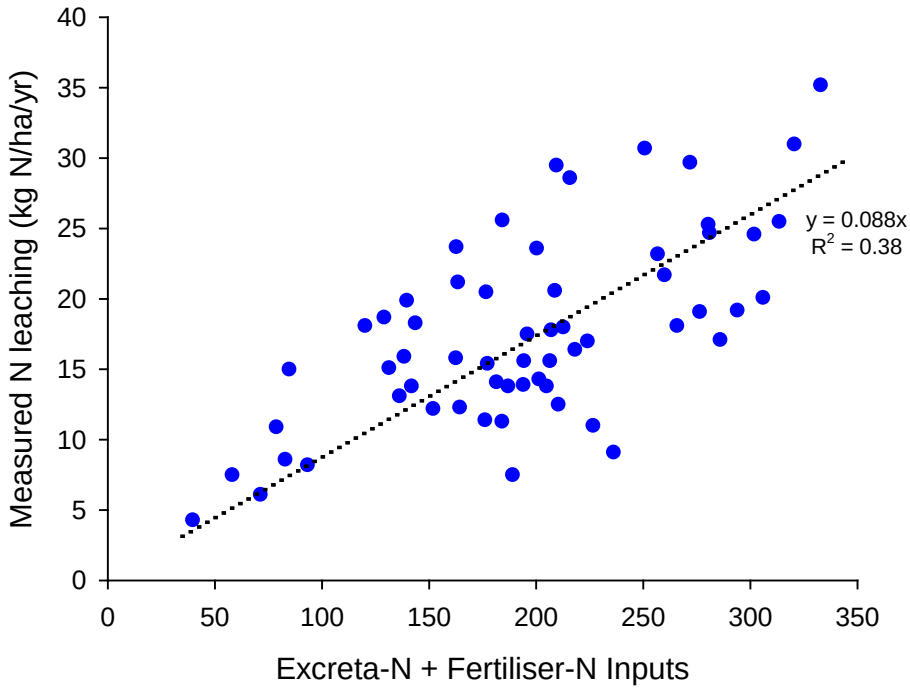


Figure 3: Relationship between N leaching loss (kg N/ha/yr) calculated using excreta + fertiliser N input (kg N/ha/yr)

4.2.3 Cropping systems

There was large variation in fertiliser-N inputs and modelled N leaching for each crop type and across regions. This variation in modelled N leaching for cropping was closely linked with drainage. Thus, minimal drainage volumes during crop growth often resulted in low leaching and substantial high residual soil N after the crop was harvested. Residual soil N was carried over and potentially leached under the next crop. This demonstrated the need to estimate $Frac_{LEACH}$ for multiple crops and rotations over several seasons to cover the low/high N leaching risk periods of the season.

Nitrogen inputs and corresponding N leaching loss for cropping rotations representative of different regions (refer to Table 1 in Section 3.2.3 for detailed description of cropping rotations) are presented in Table 10. As noted in Section 3.2.3, we have included the estimates of N inputs from the mineralisation of SOM from OVERSEER, and to provide a value for $Frac_{LEACH}$, that includes SOM mineralised N inputs (Table 10). Including SOM as an N input reduces the value of $Frac_{LEACH}$, although its contribution to $Frac_{LEACH}$ is relatively small (~-0.015). As described above, this would be representative of where the steady state of SOM has not yet been reached due to a change in land use. We recommend using $Frac_{LEACH}$ excluding mineralisation of SOM but suggest there is a need for a more critical review of the assumptions and data available to understand the contribution of SOM mineralisation to N leaching.

Estimates of $Frac_{LEACH}$ (i.e. Leached-N/[fertiliser-N + crop residue-N]) values varied between regions with values of 0.15, 0.07, 0.09 and 0.16 for Auckland, Hawke's Bay, Canterbury and Southland, respectively. The NZ-weighted average $Frac_{LEACH}$ (0.10) from the modelling was lower than the average calculated from the field experiments ($Frac_{LEACH}$ 0.26), This is expected because only N fertiliser inputs were accounted for in the measured N leaching measurements, whereas crop residues is included in the modelled $Frac_{LEACH}$ (refer to section 4.1.2). Residue N values predicted by OVERSEER agreed with values calculated using the Inventory method and current crop factors. OVERSEER undergoes improvements as better information becomes available. We recommend that MPI uses the most up to date crop factors from OVERSEER as they come available. If additional crops are included in the inventory in the future, OVERSEER includes a more extensive range of crops that could be utilised.

It is important to recognise that care is required in interpreting and comparing the modelled leaching amounts with those measured in the field. There are relatively few field trials covering a limited number of crops and locations. As most of the experiments were not designed to estimate N leaching losses from normal cropping practice, they included treatments with over application of N and water which increased the N leached. In contrast, fertiliser-N application in the model was based on good management practice, hence the risk of N loss via leaching was lower. This was largely a function of the large contribution of N from the crop residues and mineralisation of soil organic matter to N leached modelled by OVERSEER (Table 10).

Table 10: : Nitrogen (N) inputs (fertiliser, crop residue), N leaching and $Frac_{LEACH}$ (i.e. ratio of leached-N to N inputs) for four regions across New Zealand (Auckland, Hawke's Bay, Canterbury and Southland) for each crop rotation over the 1-year season modelled by OVERSEER.

Region/soil/climate	Crop rotation	Nitrogen inputs (kg/ha)				FracLEACH	
		Fertiliser	Residue	SOM Mineralisation	Leached-N (kg/ha)	Leached-N/(fertiliser-N+residue-N + SOM-N)	Leached-N/(fertiliser-N+ residue-N)
Auckland (Pukekohe)							
Soil:Patumahoe	Rotation 1	110	177	30	39	0.12	**0.14**
Rainfall: 1286 mm/yr	Rotation 2	230	56	34	33	0.10	**0.12**
Av. Temp: 14.6°C	Rotation 3	340	151	39	76	0.14	**0.15**
PET: 847 mm/yr	Rotation 4	341	77	39	100	0.22	**0.24**
	Rotation 5	301	307	38	52	0.08	**0.09**
Hawke's Bay							
Soil: Hastings	Rotation 1	230	301	32	2	0.06	**0.06**
Rainfall: 739 mm/yr	Rotation 2	280	110	30	10	0.02	**0.03**
Av. Temp: 13.6°C	Rotation 3	180	425	31	36	0.06	**0.06**
PET: 959 mm/yr	Rotation 4	60	48	28	13	0.09	**0.12**
Canterbury							
Soil: Templeton	Rotation 1	120	293	24	35	0.08	**0.08**
Rainfall: 730 mm/yr	Rotation 2	54	26	22	6	0.06	**0.07**
Av. Temp: 11.2°C	Rotation 3	147	56	25	12	0.05	**0.06**
PET: 842 mm/yr	Rotation 4	191	105	18	30	0.10	**0.10**
	Rotation 5	151	69	21	30	0.12	**0.14**
Southland							
Soil: Braxton	Rotation 1	71	25	39	15	0.11	**0.16**
Rainfall: 1122 mm/yr	Rotation 2	70	0	39	16	0.14	**0.22**
Av. Temp: 10.1°C	Rotation 3	0	70	43	20	0.18	**0.29**
PET: 735 mm/yr	Rotation 4	179	100	36	28	0.09	**0.10**
	Rotation 5	400	70	44	28	0.05	**0.06**

4.2.4 Comparison with estimates from Environment Aotearoa (2019)

Environment Aotearoa (2019) was developed to provide an overview of the state of the environment. It includes an indicator of N leaching from livestock, with specifics of the model outlined in https://www.stats.govt.nz/indicators/nitrate-leaching-from-livestock and was based on Dymond et al. (2013). The model provides estimated average values of N leaching per animal livestock type (dairy cows, sheep, cattle) for different regions of NZ, which remain constant over time. Data was derived from an earlier version of the OVERSEER model (Version 6). For example, for dairy animals, these values averaged 18-24 kg N/animal/yr for various NZ regions, except for Southland and the West Coast South Island where it averaged 12 and 39 kg N/animal/yr, respectively. Thus, it does not account for differences in farm system and management inputs on farms and so cannot be directly compared with estimates presented in this report. However, it can be used for generic comparisons.

Data on dairy animal numbers in the model are higher (by about 20-60%; presumably reflecting differences in regional boundaries and accounting for dairy replacement animals) than those for dairy cows in regions across NZ from national dairy statistics (LIC/DairyNZ, 2019). When animal numbers were scaled down by this factor to approximate corresponding dairy cow numbers and then multiplied by the number of cows per hectare the N leaching results were similar to those estimated using data described in section 4.2.1.1 on regional dairy statistics (Table 11). Note that the DairyBase estimates were for 2017/18, while the Environment Aotearoa (2019) estimates were for 2016/17 (due to only some years being covered) but the changes over time were relatively small (Table 2).

Table 11: Summary of estimates of N leaching (kg N/ha/yr) from dairy farms in different regions of New Zealand, as estimated from DairyNZ DairyBase data for 2017/18 using OVERSEER-Science model compared to that for 2016/17 using the Environment Aotearoa model (data was adjusted to common dairy cow stocking rates).

	DairyBase (OVERSEER)	Env. Aotearoa (2016/17)
Waikato	33	38
Taranaki	45	46
Canterbury	53	43
Southland	53	52

A similar comparison was made for sheep and beef farms. Regional data was collected from the Environment Aotearoa model relating to the region assumed for the different Beef+LambNZ farm classes. Data for total sheep and cattle in the region and average N leaching per animal from the Environment Aotearoa model were used to compare with data calculated using OVERSEER for specific farm classes (Table 12). This showed similar estimates using both models, although in some cases it was higher for one model than another but with no consistency. The observed variability is likely to be related to the different methods of summarising animal data, differences associated with farm system

practices captured by the OVERSEER model only, and some variation in soil and climate data associated with regions.

Table 12: Summary of estimates of N leaching (kg N/ha/year) from sheep and beef farms in different farm classes and regions of New Zealand, as estimated from Beef+LambNZ data for 2017/18 using OVERSEER-Science model compared to that for 2016/17 using the Environment Aotearoa model.

	Beef+LambNZ (OVERSEER)	Env. Aotearoa (2016/17)
Class 1: South Island high country	3	2
Class 2: South Island hill country	9	5
Class 6: South Island intensive	10	11
Class 3: North Island hard hill country	7	12
Class 4: North Island hill country	20	19
Class 5: North Island intensive	13	17

5. Conclusions and Recommendations

The review has provided data from field trials where N leaching was measured and it was strongly correlated with N leaching calculated using the OVERSEER model, thereby indicating that OVERSEER gives a reasonable prediction of N leaching. OVERSEER was then used across a range of regions and farm systems to estimate N leaching across farms in NZ and to obtain estimates of weighted average values for $Frac_{LEACH}$ for dairy, sheep & beef, and arable/vegetable cropping systems.

The analysis indicated that, for calculating N leaching and $Frac_{LEACH}$, the most effective grazed pastoral farming system data (i.e. with the highest level of correlation) was the sum of N inputs from animal excreta and fertiliser-N. For arable/vegetable cropping systems, fertiliser N and inputs from crop residues are required. Thus, the following equations are recommended for calculating $Frac_{LEACH}$ for grazed pastures (dairy and sheep and beef) and cropping systems (arable/vegetable):

$$\textit{Grazed pastoral systems } Frac_{LEACH} = (\textit{Leached N})/ (F_{SN} + F_{ON} + F_{PRP})$$

$$\textit{Cropping systems } Frac_{LEACH} = (\textit{Leached N})/ (F_{SN} + F_{ON} + F_{PRP} + F_{CR})$$

where Leached N is the measured or modelled annual quantity of N leached from the agricultural system (kg N/year), F_{SN} is the amount of N applied in synthetic nitrogen fertiliser (kg N/year), F_{ON} is the amount of N applied in the non-manure component of organic fertilisers (kg N/year), F_{PRP} is the amount of N applied in manure deposited by grazing livestock in pasture, range and paddock (kg N/year), F_{CR} is the amount of N contributed by decomposition of crop residues left on fields (kg N/year).

This analysis indicated some differences between land-use activities in NZ-weighted average $Frac_{LEACH}$ values. Based on the NZ GHG inventory methodology currently employing a uniform $Frac_{LEACH}$ value of 0.07 for dairy, sheep & beef, and arable/vegetable cropping systems, this study proposes the following three options could be considered in refining the $Frac_{LEACH}$ value, which are briefly outlined below:

1. **$Frac_{LEACH}$ based on measured N leaching data.** Based on limited grazing studies with measured N leaching loss data the $Frac_{LEACH}$ value could be 0.07 for grazing systems (dairy and sheep and beef systems) and 0.26 for arable/vegetable cropping systems. We would advise caution on using $Frac_{LEACH}$ values based on a limited number of studies in confined catchments for national GHG calculations.
2. **$Frac_{LEACH}$ based on land-use activity.** The $Frac_{LEACH}$ values could be separated by land-use activity and this would result in $Frac_{LEACH}$ values of 0.08 for dairying, 0.08 for sheep and beef and, 0.10 for arable/vegetable cropping systems. While the $Frac_{LEACH}$ values are the same for dairy and sheep and beef systems, issues relating to separating the fertiliser N inputs between these two systems is likely to be difficult to currently implement for national GHG calculations.
3. **Single $Frac_{LEACH}$ value for grazing (i.e. covering both dairy and sheep and beef, as well as others such as deer and goats) and separate value for arable and vegetable cropping systems**. A single $Frac_{LEACH}$ value for grazing (dairy and sheep and beef; 0.08) and a separate value for cropping systems (0.10) could be considered. This option would negate issues about separation of fertiliser N inputs between dairy and sheep and beef farm systems for national GHG calculations.

In summary, our primary recommendation is to use a single $Frac_{LEACH}$ value of 0.08 for grazing systems (covering both dairy and sheep and beef systems, as well as could be considered for others such as deer and goats) and a separate $Frac_{LEACH}$ value of 0.10 for arable and vegetable cropping systems (Option 3).

It is important to recognise that the $Frac_{LEACH}$ value for cropping systems should be interpreted with caution because of uncertainties associated with predicted leaching values by OVERSEER. It is also recognised that there is some spatial variability associated with site factors such as soil and rainfall/drainage, farm system intensity and crop rotations and management. However, it is unrealistic to recommend a complex modelling system for estimating N leaching since only a limited range of input data is available for use within the national GHG inventory. The above recommended values were based on nationally weighted average values that accounted for regional variations in farms and animal or crop production across NZ. Furthermore, they also showed little variation over time during the last decade (based on analyses over three-time intervals) within the dairy and sheep and beef farm systems, indicating reasonable stability in these average $Frac_{LEACH}$ values.

Other animal production systems in NZ include deer and goat farming, although these are minor compared with sheep & beef farms. For deer and goat farming systems, it is recommended that the same $Frac_{LEACH}$ value is used as for sheep & beef (0.08). Their methods of production are reasonably closely aligned to sheep & beef farming and the methods for estimating N excretion are similar until further research is undertaken.

5. Further Research

Refine pasture N concentration used in the NZ Inventory on calculated $Frac_{LEACH}$ value

One aspect identified in this study, that was not considered in the previous assessment for $Frac_{LEACH}$ of Thomas et al. (2002), was the use of the single diet N concentration values that are used in the NZ Inventory. This ensures the diet N concentrations aligns with the amounts of N excreta calculated in the Inventory, rather than the excreta-N estimated in OVERSEER, which accounts for differences in pasture N concentration as well as in brought-in feed sources. Brought-in feed sources are not accounted for within the NZ Inventory. The effects of this were most evident in the sheep and beef farm systems where the higher N concentration in pasture estimated in OVERSEER led to approximately 20% higher values for the amount of N excreted per hectare compared to those using Inventory-based estimates of excreta-N. In contrast, effects were minor for dairying, partly due to a smaller difference in pasture N concentration between the two methods coupled with the countering effect of lower N concentrations in brought-in feeds used on dairy farms.

It is recommended that future research to refine the *$Frac_{LEACH}$ value* is carried out using updated estimates of pasture N concentration in the NZ Inventory based on a review of pasture N concentration.

Fertiliser activity data and implications on calculated $Frac_{LEACH}$ value

If a disaggregated sector based $Frac_{LEACH}$ is applied, it will be necessary to disaggregate the fertiliser N input data. Two potential sources of this information are the fertiliser industry (Fertiliser Association of NZ) and data collected by the Statistics NZ. It is not clear whether this sector-data currently exists or is available.

We know that Statistics NZ collects fertiliser data through the Agricultural Production Statistics, but it is limited to a few N products: urea/urease coated urea, DAP, ammonium sulphate. While this may be suitable for capturing most of the fertiliser applied to pastoral land, arable and vegetable growers use a much wider range of N products e.g. CAN (27% N) used in our modelling is not specifically captured by Statistics NZ. Based on the 2017 Census data for vegetable production area and the amount of N fertiliser attributed to vegetable production, the average N was 117 kg N/ha/year, whereas the average application used in our modelling was 50% higher (181 kg N/ha/year). Poor N fertiliser data could result in less accurate estimates of N_{LEACH} for at least the cropping sector.

Crop data and modelling:

- Explore using more suited crop modelling platform in the future that are better set up for simulating cropping rotations.
- Field studies designed to quantify N inputs and outputs over rotations to increase our confidence in the N_{LEACH}.
- Update crop factors used in OVERSEER as they come available in the future.

Review of the contribution of mineralisation of SOM

Currently, the contribution of mineralisation of SOM in cropping systems is assumed to be zero when there is no change in land use (Crop remaining crop), calculated in LULUCF unless there is a change from annual to perennial crop or vice versa. Hence, the assumption is that in cropping systems soil C stocks do not change (i.e. they are in an equilibrium state). This may need to be challenged as this might not be the case. Williams et al, (2000) noted that equilibrium could take 70 years for some intensively farmed soils, and our modelling using OVERSEER suggests that these soils had not reached an equilibrium state.

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8. Appendices

8.1 Literature review of New Zealand trials measuring nitrogen leaching from grazed pastures

This review is based on Watkins and Shepherd (2014) who provided a summary of NZ pasture farmlet studies measuring N leaching loss based on research undertaken up to 2015.

The literature review was carried out to establish a list of grazed pasture experiments within NZ where N leaching was measured under grazing which were directly relevant to assessing the $Frac_{LEACH}$ parameter used to estimate the proportion of N applied to agricultural land that is lost through leaching and run-off via indirect N_2O emissions from nitrate leaching. Therefore, experiments measuring N leaching comprising of large plots or paddocks or farmlets that were managed as part of the farm system were the primarily focus of the review. Note that these will be different to a wider research dataset that includes paddock, small-plot and lysimeter studies not used in this review but that would be used for comprehensive validation of the OVERSEER model. The location of most of these farm system experiments measuring N leaching were generally confined to three regions – Waikato, Manawatū, and Southland, with fewer experiments undertaken in Canterbury, Otago and Southland regions. The three main methods used to determine N losses in these trials are: porous ceramic cups buried below the root zone, intact soil cores (lysimeters) buried in the paddock with their drainage collected, and hydrologically isolated catchments where drainage from the entire catchment was sampled. This list includes trials designed to measure the N leaching losses (kg/ha) across the entire farm system, not trials looking at leaching from specific areas such as urine patches.

8.1.1 Dairy cow nitrogen leaching studies

Because of the high potential N leaching losses, the majority of NZ farm system experiments that included N leaching measurements were carried out on dairy farms. Experiments to date have focussed on the effects of stocking and N fertiliser rates, a range of mitigation options to reduce N leaching (such as wintering off, dicyandiamide (DCD) application and strategic grazing) and the impact of effluent applications on N leaching (Table A1). Nitrogen leaching within these experiments was measured using either hydrologically isolated plots or porous ceramic cups, depending on the soil type.

One of the first farmlet experiments investigating N leaching losses under dairy farm systems was carried out on DairyNZ's No.2 Dairy Farm, Hamilton (1993-97). This experiment measured the impact of different application rates of N fertiliser (0, 200 and 400 kg N/ha/yr). Porous ceramic cups sampled soil water at 1000 mm depth. This experiment showed that N leaching increased with higher N fertiliser application rates. The average concentration of nitrate-N leached was 9, 12 and 22.5 mg/L for the 0, 200 and 400 kg N/ha fertiliser treatments respectively over a 2-year (1993-1994) period (Ledgard et al., 1996). Further data was published in 1999 (Ledgard et al., 1999). In 1998 the farmlets were reorganised to investigate the impact of stocking rate on N leaching (Sprosen et al., 2002). The same porous ceramic cup methodology was used in this trial which consisted of five farmlets with the following stocking rates, 2.2, 2.7, 3.2, 3.7 and 4.3 cows/ha on a free draining allophanic soil. It was concluded in the paper, that stocking

rate may be a poor indicator of N leaching with limited imported feed, given that N leaching tended to be higher at lower stocking rates in this experiment (Sprosen et al., 2002).

An experiment similar to the early No.2 Dairy trials was established in Southland near Edendale in 1996, using hydrologically isolated plots to measure N leaching from the drained clay soil. During the initial year of the experiment, no N fertiliser was applied (Monaghan et al., 2002). Non-lactating dairy stock rotationally grazed the plots (2.3 cows/ha) from November 1995 to late-May 1996 and no winter grazing occurred. During the initial year (1995-96), the amount of nitrate-N lost in drainage water was 25 kg N/ha (Monaghan et al., 2002). In the following years the experiment investigated the impact of N fertilisation (0, 100, 200 and 400 kg N/ha/yr) and stocking rates on N leaching during 1996-99 (Monaghan et al., 2005). As in the previous experiment, the plots were rotationally grazed by non-lactating dairy stock, at approximately four-week intervals from August to May and no winter grazing occurred. The results showed that increasing N fertiliser and stocking rate resulted in a significant increase in the amount of N leaching. The mean N leaching rate over the course of the experiment was 30, 34, 46 and 56 kg N/ha/year, for the 0, 100, 200 and 400 kg N fertiliser treatments respectively (Monaghan et al., 2005). These authors noted that the results of this trial may not accurately reflect those in a system that has been in long-term (>20 years) equilibrium, as this trial site had recently undergone conversion from sheep to cattle farming and an improvement in soil fertility had occurred (Monaghan et al., 2005).

The longest running dairy farmlet experiment in New Zealand investigating N leaching is the Tussock Creek experiment in Southland. This experiment has tested a range of management options to reduce N leaching under dairy farm systems. Hydrologically isolated plots were established in 1999, and the effects of various grazing strategies were tested 2000-2003 (Monaghan et al., 2016). N leaching loss was 21, 25, 20 and 11 kg N/ha from 2000 to 2003. Restricted autumn grazing reduced N leaching by 42-60%. From 2004, the site was used to test the effects of DCD (Monaghan et al., 2009), although this work has stopped since the withdrawal of DCD from the market. The results showed that DCD reduced the amount of N in drainage water by between 21 and 56% (2004-2007). Over the 4-year period, 13 kg N/ha and 7 kg N/ha was measured in the drainage water from the control and DCD treatments respectively (Monaghan et al., 2009). Data from later years is currently being written up (C. Smith, pers. comm.).

Further north, in Otago, a farmlet experiment (Kelso) measured the impact of effluent application on nutrient losses in hydrologically isolated plots over 3 years (2000-2003) (Monaghan & Smith, 2004). This experiment showed that if effluent was applied when the maximum depth of application exceeded the soil water deficit, relatively large concentrations of ammonium-N, total-P and E. coli were found in the resultant drainage (Monaghan & Smith, 2004).

In Canterbury, the Lincoln University Dairy Farm (LUDF) has in-paddock lysimeters (50 cm diameter by 70 cm deep) that are used to measure nitrate-N leaching losses from grazed pasture. Data has been collected since 2002. Lysimeters contain either Templeton sandy loam above sand/gravel or Eyre stony silt loam above gravel. About two thirds of the lysimeters receive effluent (K. Cameron, pers. comm.).

In 2009, Christensen (2012) began a controlled grazing study in the Manawatū. In this experiment, plots were hydrologically isolated with mole and tile drainage systems and

the two grazing practices were: Restricted (4 hours per day or night grazing) or standard (6 hours per day or 12 hours per night). The results showed that duration-controlled grazing could reduce N leaching by more than 50% (Christensen et al., 2019).

Another long-term source of data has been a sequence of farmlet experiments at DairyNZ's Scott Farm near Hamilton. These have investigated 'strategic grazing', along with a variety of other mitigation strategies to reduce N leaching and improve N use efficiency, The first of this sequence was the Resource Efficiency Dairying trial (RED trial': (Ledgard et al., 2006). One part of this trial looked at the impact of utilising a stand-off pad over winter and found a 25% reduction in N leaching compared to the control farmlet (Ledgard et al., 2006). A modification of the RED trial continued 2007-2009, known as the 'Tight N' farmlet study. This included nil N, 'conventional' (i.e. a typical Waikato production system) and stand-off treatments. Any differences between treatments were overshadowed by the effect of changes in rainfall between years. An extremely wet 2008 resulted in N leaching ranging from 21 kg N/ha in 2007 to 98 kg N/ha in 2008 and back to 21 kg N/ha in 2009. Full results are currently being summarised for publication (M. Shepherd., pers. comm.). In 2011, this site developed two new farmlets ('current and future'), which ran until 2015 as part of the Pastoral 21 programme and are described later in this paper. There has therefore been a long run of measurements made across this site over several soil types. Productivity measurements from nil N farmlet for the nine years of the RED and Prototype experiments have been reported by Glassey (2013).

Four farmlet experiments were established as part of the Pastoral 21 research programme, which started in winter 2011. The farmlets were designed to compare a 'current system' representative of the region and a 'future system'. The 'future system' was designed to reduce minimise nutrient (N and P) losses while maintaining profitability. Three of the farmlets involved direct measurements of nitrogen leaching using either porous cups (Waikato) or hydrologically isolated catchments (Manawatū and Southland). 'Current system' leaching losses from the free draining Waikato soils were much higher than from the heavier Manawatū and Southland soils (average of 54 vs 19 kg N/ha respectively). The 'future' systems reduced annual N leaching by approximately 40% in the Waikato and Manawatū, and by 27% in Southland (Shepherd et al., 2017). Detailed information on individual farmlets can be found in Beukes et al. (2017), Hedley et al. (2017) and Dalley et al. (2014).

Table A1: Summary of dairy farmlet grazing studies with paddock-scale nitrogen (N) leaching measurements across regions of New Zealand. Summary includes brief description, soil type, annual rainfall and study duration.

Site	References	Brief description	Soil type	Annual rainfall (mm)	Study period
Southland					
Tussock Creek	Monaghan et al. 2016	Effectiveness of various grazing strategies on N leaching.	Pallic soil	900-1150	2000-03
Tussock Creek	Monaghan et al. (2009)	Effectiveness of DCD in reducing N leaching from a grazed dairy pasture.	Pallic soil	1097-1257[2]	2004-13
Edendale	Monaghan et al. (2002; 2005)	Impact of N fertilisation and stocking rate on N leaching.	Pallic and Brown soils	804-1017	1996-99
Otago					
Kelso	Monaghan & Smith (2004)	Impact of effluent application on nutrient losses in hydrologically isolated plots.	Pallic soil	c. 880	2000-03
Telford	Dalley et al. 2014 Shepherd et al. (2017)	P21 farmlet trial. Animals housed off paddock for periods	Pallic soil	c. 730	2011-16
Canterbury					
LUDF	Unpublished	In-paddock lysimeters monitoring farm N leaching losses, 2 soil-types and ± effluent	Recent and Pallic soil	c. 600	2003-09
Manawatū					
Massey Uni.	Christensen et al. (2012)	Controlled-duration grazing trial investigating impact on N, P and faecal microbes in drainage and runoff.	Pallic soil	c. 1000	2009-11
Massey Uni.	Hedley et al. (2017) Shepherd et al. (2017)	P21 farmlet trial, investigating impact of feed pads and controlled-duration grazing on nutrient losses.	Pallic soil	c. 1000	2011-16
Waikato					
Ruakura	Ledgard et al. (1996; 1999)	Investigating the fate of N with varying stocking rates and N fertiliser application.	Allophanic soil	1033-1421	1993-96

Site	References	Brief description	Soil type	Annual rainfall (mm)	Study period
Ruakura	Sprosen et al. (2002)	Impact of four stocking rates on N leaching.	Allophanic soil	1000	1999-00
Scott Farm	Ledgard et al. (2006)	'RED' trial investigating mitigation practices to reduce N leaching.	Allophanic, Gley and Podzol soils	c. 1100	2001-05
Scott Farm	Glassey, 2013 and unpublished	Continuation of the 'RED' trial – nil N, control and standoff treatments.	Allophanic, Gley and Podzol soils	c. 1100	2007-09
Scott Farm	Beukes et al. (2017) Shepherd et al. (2017)	P21 farmlet study, investigating various stocking rates, N fertiliser rates and use of stand-off pads on nutrient losses.	Allophanic, Gley and Podzol soils	c. 1100	2011-2016

8.1.1.1 Nitrogen leaching losses from wintering-off grazing practises

Dairy cow wintering-off grazing practises are common in Canterbury, Otago and Southland regions of NZ. Wintering-off grazing is when non-lactating dairy cows are moved from pasture to graze forage crops such as swedes (*Brassica napus*), fodder beet (*Beta vulgaris*) or kale (*Brassica oleracea*) typically at high animal stocking rates over a 10-week period during winter (Monaghan et al., 2013). This practise results in large amounts of excretal N being deposited onto bare soil, which is left fallow for extended periods during winter until pasture/crop establishment in spring. Wintering-off grazing is important to consider in association with N leaching losses from pasture since wintering grazing typically has high N losses relative to N leaching losses from pasture and therefore needs to be accounted for in dairy farm systems located in Canterbury, Otago and Southland regions of NZ (Monaghan et al., 2013).

Smith et al. (2012) carried out a 3-year leaching study (2009 to 2011) in northern Southland (NZ) using porous ceramic cup samplers under winter grazed forage crops using swedes (year 1), swedes and turnips (Year 2) and fodder beet (Year 3) on a free-draining Lintley Orthic Brown soil. Annual N leaching losses were variable, ranging from 8.5 to 103 kg N/ha over the 3-year study and averaged 78 kg N/ha over the entire study period. A three-year leaching study (Monaghan et al., 2013) using hydrologically isolated plots in a Pallic soil to measure N leaching loss from dairy cows winter grazing a kale forage crop was conducted in Southland, NZ. The study showed that nitrate leaching loss from the winter grazed kale crop averaged 52 kg N/ha over the 3-year study period (annual losses were 79, 34 and 44 kg N/ha for 2006, 2007 and 2008, respectively).

Recently, a 2-year grazing study (Smith and Monaghan, in press) at the southern Dairy Hub research farm in Southland investigated N leaching losses using porous ceramic cup samplers from autumn and winter grazed fodder beet and kale treatments on a well-drained Edendale typic firm brown soil. Leaching losses for fodder beet from autumn-grazed was approximately 70-130 kg N/ha compared to 40-80 kg N/ha for winter-grazed fodder beet across the 2-year study period. Leaching losses from winter-grazed kale were approximately 2-fold higher than fodder beet across both measurement years.

Average data from these wintering crop systems was used in calculations to get whole-system N leaching for dairy cow farm systems in Canterbury, Otago and Southland for the regional farm system estimates (section 4.2.1.1 and 4.2.1.2).

8.1.2 Sheep and beef nitrogen leaching studies

Only a limited number of experiments that included farmlet scale measurement of N leaching have been carried out on sheep and beef farms in NZ (Table A2). One of the earliest farmlet experiments investigating N losses under sheep grazing was carried out at AgResearch Grasslands (Palmerston North) by Ruz-Jerez *et al*. (1995) during the years 1989-91. Nitrogen leaching was measured under three pasture types; perennial ryegrass and white clover pasture, herbal ley, and ryegrass + 400 kg N/ha/yr. Pastures were grazed by sheep at a stocking rate which varied with feed availability. The amount of N leached was calculated as the product of the estimated volume of water draining below 450 mm and the nitrate-N concentration in the soil between 300-450 mm depth. Under all three

pasture treatments at the beginning of the experiment, nitrate-N concentrations were high, most likely due to mineralisation of organic N associated with soil disturbance during pasture establishment. After the initial effect of soil cultivation had disappeared, nitrate-N concentrations in the soil solution for the ryegrass + 400 kg N/ha/yr treatment were generally much higher and more variable than for the clover-based pasture. The total amount of N lost by leaching during 1990 (May-August) was calculated as 6, 7 and 41 kg nitrate-N/ha for the clover-based, herbal ley and ryegrass + 400 kg N/ha/year treatments, respectively (Ruz-Jerez *et al*., 1995).

Several N leaching trials were run at Ballantrae using mini-lysimeters buried 300 mm in sheep grazed paddocks to provide leachate samples for N analyse and to measure drainage volumes. Issues with the use of buried mini-lysimeters are discussed in Hoogendoorn et al. (2017). In 2010 a mini-lysimeter trial was established at Ballantrae to examine losses of nitrogen and carbon from low and medium sloped areas in sheep grazed north island hill country. Results for 2010-2013 showed N leaching in non-N fertilised lysimeters of 15-28 kg N/ha/yr.

In the late 2000s when the Waikato Regional Council investigated setting an N-cap for the management of Lake Taupō water quality, an influx of research occurred within this catchment. The catchment was predominantly sheep and beef farms and therefore a number of trials were established focussing specifically on sheep, beef and deer farm operations on free-draining pumice soils, investigating expected N leaching rates under land with different stock and various mitigation options.

Betteridge *et al*. (2007) established a trial (2002-04) in the Taupō catchment assessing the ability to reduce N leaching in a cattle farming situation by grazing off cattle during the winter months. Two farmlet trials were established; cattle grazed on pasture all year round (AYG) and no winter grazing (May until early September) (NWG). Nitrogen leaching was measured using ceramic cup soil solution samplers inserted at 600 mm depth. The AYG farmlet leached more N than the NWG farmlet, the mean over the three years was 12 and 4 kg nitrate-N/ha/yr, for the AYG and NWG farmlets respectively. This indicated that removing cattle over the winter period reduced annual N leaching from that property.

In 2007 a cattle grazing trial was established on the western side of Lake Taupō to investigate possible strategies to reduce N leaching. There were five treatments: control, high sugar grass (HSG), nitrification inhibitor (DCD), diuretic drench (salt) and steers instead of female cattle. N leaching samples were collected using ceramic suction cup samplers at 600 mm depth. Results from the first year showed a significantly larger amount of N was leached in the renovated pasture (HSG) compared to the control (63 vs 8 kg N/ha for the HSG and control treatments, respectively; Betteridge et al., 2011). The difference was attributed to the increase in N mineralisation associated with pasture renewal. Overall leaching levels in 2008-2010 were relatively low with few clear treatment differences and an average from the control treatment of 15 kg N/ha/yr (Ledgard et al., unpublished).

Table A2: Summary of sheep and beef farmlet experiments with paddock-scale nitrogen (N) leaching measurements across regions of New Zealand.

Site Name	Publication	Brief description	Soil type	Annual rainfall	Study period
Manawatū/Wairarapa					
Grasslands	Ruz-Jerez *et al*. (1995)	N leaching under clover-based pasture and N fertilised pasture grazed by sheep	Recent soil	950 mm	1989-91
Ballantrae	Hoogendoorn & Lambert (2017)	N fertiliser and N leaching in intensively managed sheep grazed hill country	Brown soil	1270 mm	2005-08
Ballantrae	Hoogendoorn & Devantier (2011)	Impact of grazing intensification and slope on nutrient losses in sheep grazed hill country	Brown soil	1270 mm	2010-13
Waikato					
Lake Taupō	Betteridge *et al*. (2007)	All round grazing vs. wintering off	Pumice soil	1400 mm	2002-04
Lake Taupō	Betteridge *et al*. (2011)	N leaching under undisturbed control pasture and high sugar ryegrass	Pumice soil	1400 mm	2007

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8.2 Literature review of New Zealand trials measuring nitrogen leaching from arable and vegetable cropping systems

We have compiled a list of references and summarised the amounts of fertilier-N applied and leached under a range of different vegetable and arable crops in New Zealand (Tables A3-A8). The measured or estimated amounts of nitrogen leached varied considerably: 6-292 kg N/ha for vegetable crops and 1-142 kg N/ha for arable crops. The review highlighted that:

- The leaching figures quoted were not always associated with inputs for the crop being grown at time of the leaching measurement. Deciding which inputs were associated with a given leaching event was not straight forward.
- On some occasions periods of dry weather resulted in low leaching events, which caused the soil nitrogen to be carried over to the following season and leached under the next crop; hence the inputs do not always line up with reported leaching events.
- Methods to measure nitrate leaching varied considerably across experiments – the majority of studies used modelled outputs or were measured with soil solution samplers.
- Drainage fluxmeters (Norris et al. 2017) were on-farm based measurements rather than controlled research experiments.
- Most experiments conducted were of short-term duration i.e. 1 year (with the exception of Norris et al. (2017) which extended over 2 years and Fraser et al. (2013) which extended over 7 years.
- There appears to have been some reduction in the amounts of N fertiliser applied to some crops (especially potatoes) in more recent years as compared to the amounts applied 20+ years ago.

Table A3: Amounts of nitrogen applied and amounts of nitrate leached from vegetable crops, the region where measurements were made and the measurement method used as reported in a range of references for New Zealand conditions.

Crop	Reference	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)	Region	Measurement method
Intensive vegetables	Williams *et al.* 2003	0	13-144	Pukekohe	Soil solution samplers/drainage calculations
(Spinach)	Williams *et al.* 2003	200	80-236	Pukekohe	Soil solution samplers/drainage calculations
	Williams *et al.* 2003	400	119–292	Pukekohe	Soil solution samplers/drainage calculations
Intensive vegetables	Francis *et al.* 2003	64-150	73–173	Pukekohe	Soil solution samplers/drainage calculations
Cabbages	Williams and Tregurtha 2003	80	178	Pukekohe	Soil solution samplers/drainage calculations
Broccoli	Williams and Tregurtha 2003	21-25	11-91	Ōamaru	Soil solution samplers/drainage calculations
Spinach	Williams and Tregurtha 2003	40	246	Pukekohe	Soil solution samplers/drainage calculations
Intensive vegetables	Green and Clothier 2009	*NA*	11–80	Canterbury	Modelled for a range of regional soils and climates
Intensive vegetables	Fenemor *et al.* 2016	*NA*	16–51	Tasman, Waimea Plains	Modelled for a range of regional soils
Intensive vegetables	Norris *et al.* 2017	*NA*	118–212	Manawatū	Drainage fluxmeters
Maize	Gentile *et al.* 2014	100	6.6 (1-21)	Poverty Bay Flats	Modelled for a range of regional soils
Squash	Gentile *et al.* 2014	150	10.9 (4-39)	Poverty Bay Flats	Modelled for a range of regional soils
Broccoli/Lettuce	Gentile *et al.* 2014	80	15.5 (10-34)	Gisborne, Poverty Bay Flats	Modelled for a range of regional soils
Potatoes	Martin *et al.* 2001	0-472	208–219	Pukekohe	Soil solution samplers/drainage calculations
Potatoes	Williams and Tregurtha 2003	259 & 469	111–171	Pukekohe	Soil solution samplers/drainage calculations

Table A3 continued.

Crop	Reference	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)	Region	Measurement method
Potatoes	Williams and Tregurtha 2003	111 & 120	25–65	Ōamaru	Soil solution samplers/drainage calculations
Potatoes	Francis et al. 2003	472-491	63–193	Pukekohe	Soil solution samplers/drainage calculations
Potatoes	Jamieson 2006	100-388	57-170	Canterbury	Modelled for a range of regional soils
Potatoes	Thomas et al. 2007	*NA*	25.7	Waikato, Hawke's Bay, Manawatū, Canterbury	Modelled for two soil types in each region
Potatoes	Sinton et al. 2009	239–458	40–107	Matamata	Soil solution samplers/drainage calculations
Potatoes	Thomas et al. 2012	400	127-141	Lincoln, Canterbury	Soil solution samplers/drainage calculations
Potatoes	Herath et al. 2014a	120	67.7	Manawatū	Drainage fluxmeters
Potatoes	Herath et al. 2014b	*NA*	27.8	Manawatū	Modelled
Potatoes	Norris et al. 2017	*NA*	46-60	Waikato, Manawatū	Drainage fluxmeters

where NA = not available

Table A4: Amounts of nitrate leached and region where measured (using fluxmeters) as reported by Norris et al. (2017).

Crop	Region	Nitrogen leached (kg N/ha/yr) year 1	Nitrate leached (kg N/ha/yr) year 2
Rotation	Manawatū	49.9	37.7
Rotation	Manawatū	33.7	27.6
Rotation	Manawatū	17.5	8.3
Rotation	Hawke's Bay	4.2	12.3
Rotation	Hawke's Bay	21.5	*NA*
Rotation	Hawke's Bay	9.5	21.7
Rotation	Waikato	17.2	14.5

Table A5: Amounts of nitrogen applied and amounts of nitrate leached by arable crops, region where measured and measurement method used as reported in a range of references for New Zealand conditions.

Crop	Reference	Region	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)	Measurement method
Wheat	Adams and Pattinson 1985	Canterbury	25-50	60	Periodic soil sampling
Wheat (2nd year)	Adams and Pattinson 1985	Canterbury	25-51	35	Periodic soil sampling
Peas	Adams and Pattinson 1985	Canterbury	*NA*	90	Periodic soil sampling
White clover	Adams and Pattinson 1985	Canterbury	*NA*	10	Periodic soil sampling
Wheat	Webb *et al.* 2001	Canterbury	-	43 (14-104)	Modelling
Non-leguminous crops	Francis *et al.* 1994	Canterbury	*NA*	37	Soil solution samplers/drainage calculations
Wheat (2nd year)	Francis *et al.* 1995	Canterbury	*NA*	142	Soil solution samplers/drainage calculations
Spring Barley	Eco-link 1999	Canterbury	150	60-70	-
Barley/Lupin/Maize/ Rape rotation	Stark *et al.* 2006	Canterbury	70	5.4-12.7	Lysimeters
Spring Barley	Lilburne *et al.* 2002	Canterbury	150	56	Modelled
Swedes	Shepherd *et al.* 2012	Central Plateau	200 (+ grazed)	132	Soil solution samplers/drainage calculations
Kale	Shepherd *et al.* 2012	Central Plateau	200 (+ grazed)	173	Soil solution samplers/drainage calculations
Maize	Gentile *et al.* 2014	Poverty Bay	100	1-21	Modelled
Forage brassica	Chrystal et al 2012	Southland	*NA*	71	Modelled
Fodder beet	Malcolm et al 2016	Canterbury	0	10-11	Lysimeters
Fodder beet	Malcolm et al 2016	Canterbury	250 (urine)	84	Lysimeters
Fodder beet	Malcolm et al 2016	Canterbury	300 (urine)	64	Lysimeters

Table A5 continued.

Crop	Reference	Region	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)	Measurement method
Summer turnips/ followed by autumn grass	Hanly et al 2017	Manawatū	95	12-25.3	Mole drain drainage water losses
Rotation	Norris et al 2017	Canterbury	26.2	43.4	Drainage fluxmeters
Rotation	Norris et al 2017	Canterbury	22.3	18.6	Drainage fluxmeters
Rotation	Norris et al 2017	Canterbury	7.8	10.5	Drainage fluxmeters

where NA = not available

Table A6: Amounts of nitrogen applied and amounts of nitrate leached as measured at two different depths by Beare et al. (2010) in Lincoln Canterbury, using soil solution samplers and drainage calculations.

Crop	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)	
		To 60cm depth	To 150cm depth
Maize	211	25	-
Kale	282	10	-
Barley	123	0	-
Barley/Rape/Oats	342	43	15
Barley/Oats/Ryegrass	252	26	31
Kale/Wheat	321	79	34
Kale/Triticale+bean	321	40	28
Maize/Wheat	250	73	53
Maize/Triticale+bean	250	77	53
Rape/Oats	0	43	14
Oats/ryegrass	0	15	30

Table A7: Amounts of nitrogen applied and amounts of nitrate leached as measured by Fraser et al (2013) over the course of a 7-year rotation in Lincoln, Canterbury - using soil solution samplers and drainage calculations.

Millenium Tillage Trial Year	Crop	Nitrogen applied (kg N/ha/yr)	Nitrate leached (kg N/ha/yr)
2000/01	Barley[#]	101	19.2
2001	Oats (forage)	32	
2001/02	Wheat	107	17.7
2002	Rape (forage)	0	
2002/03	Peas	15	9.1
2003	Rape (forage)	0	
2003/04	Barley	120	16.1
2004	Rape (forage)	19	
2004/05	Peas	21	8.6*
2005	Rape (forage)	15	
2005/06	Barley	176	70.8*
2006	Rape (forage)	23	
2006/07	Barley	124	9.2
2007	Rape (forage)	82	

[#]*Previous crop was long term pasture*
**2005 was a particularly dry winter and 2006 was a much wetter winter than average*

Table A8: Amounts of nitrogen applied and amounts of nitrate leached, estimated using input and output calculations by Crush et al (1997).

Crop	Nitrogen applied (kg N/ha/yr)	Calculated Surplus N (kg N/ha/yr)
Early potatoes	543	429 (282-587)
Main crop potatoes	268	92 (29-181)
Onions	241	118 (17-230)
Winter lettuce	430	286 (245-359)
Summer lettuce	370	186 (161-211)
Squash	326	238 (123-401)
Persimmons	116	26
Summer cabbage	249	168
Winter cabbage	301	242
Pumpkin	212	120

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