Trends in nitrogen loss from Canterbury dairy farms

November 2023

Authors:
Finlay Thompson
Teresa A'mar
Katrin Berkenbusch
Sadhvi Selvaraj

DRAGONFLY Data Science

PO Box 27535, Wellington 6141
New Zealand
dragonfly.co.nz

Cover Notes

To be cited as:

Thompson, F.N. and A'mar, T. and Berkenbusch, K. and Selvaraj, S. (2023). Trends in nitrogen loss from Canterbury dairy farms. Report prepared by Dragonfly Data Science for Overseer Limited. 32 p.

Cover image:

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EXECUTIVE SUMMARY

Agricultural activities, particularly dairy farming, are putting increasing pressure on New Zealand's natural environments. Some of the impacts are associated with the loss of excess nutrients and the deterioration of natural habitats, such as freshwater ecosystems. Efforts to reduce environmental impacts from dairy farming include regulatory and farm management practices that are aimed at estimating and limiting nutrient losses to the environment.

One of the tools widely used to estimate nutrient flows in agricultural farming systems in New Zealand is the model OverseerFM. The model can be used to generate predictive nutrient budget analyses and to derive estimates of potential nutrient losses (e.g., nitrogen loss), documenting the inputs and outputs to a given scale (e.g., block or farm). Owing to its widespread use, the underlying database of OverseerFM contains a comprehensive dataset of New Zealand farming systems.

The current study focused on the OverseerFM dataset from Canterbury to characterise dairy farming enterprises in this region, and to analyse estimates of nitrogen loss from Canterbury dairy farms over time. Following an initial data exploration, the study dataset was restricted to the period for the farming years 2016–17 to 2021–22. Data from 1269 farms were included in the study, representing approximately 302,000 hectares of land used for dairy production. In the most recent reporting year, 2021–22, the analysis estimated a mean of 46.2 kilogrammes of nitrogen loss per hectare from these farms, representing a 27.5% decrease from 63.8 kg per hectare in 2016–17.

Comparison with data from other sources showed that the study dataset represented a comprehensive characterisation of the Canterbury dairy industry. There was a close match between independently-reported numbers of dairy farms, total dairy production, and productive land and corresponding records in OverseerFM.

A statistical model was fit to the OverseerFM nutrient budget analysis data to assess annual trends in estimated nitrogen loss. Based on this modelling, nitrogen loss from Canterbury dairy farms was decreasing over the study period at an annual rate of 5.7% (95% credible interval (c.i.): 1.1% to 10.6%) per year, or 29.8% (95% c.i.: 6.6% to 48.9%) over six years. This decrease was estimated after the size of the Canterbury dairy industry was factored out by the model and, therefore, did not relate to any changes in dairy farm area over this period. The modelled decrease in nitrogen loss indicates changes in farming practice that were reported in OverseerFM nutrient budget analyses. Further analysis of OverseerFM data could be used to investigate this aspect.

The model was also designed to determine any variation between six geographical sub-regions (that were defined as part of the current study). This part of the analysis showed that the Ashburton sub-region had the greatest reduction in nitrogen loss, whereas the Waimakariri sub-region had the weakest evidence of a reduction. The South Canterbury sub-region had lower nitrogen loss than the other regions, after taking into account farm size.

1. INTRODUCTION

Changes in agricultural land use in New Zealand have included a substantial increase in dairy farming in the last two decades (StatsNZ, 2021a, 2021b). This change was evident in an over 80% nationwide increase in both the area of land used for dairy farming and the number of dairy cattle (between 2002 and 2019, and between 1990 and 2019, respectively). Across regions, the largest increase in dairy farming was in Canterbury, where dairy land use area increased 187.5% and dairy cattle numbers increased tenfold (973%) between 1990 and 2019. In 2021–22, dairy farming in the Canterbury region had the largest average herd size and the highest average number of cows per hectare (e.g., 3.49 and 3.36 cows per hectare in North and South Canterbury, respectively) across New Zealand (Livestock Improvement Corporation Limited and DairyNZ Limited, 2022). Similarly, the Canterbury region supports the second largest percentage of all cows milked in New Zealand (20%), behind Waikato (22.3%).

The notable conversion from sheep and cropping to dairy farming in Canterbury started in the early 1980s, and was accompanied by concomitant increases in both per cow and per hectare milk production (Pangborn & Woodford, 2011). Both farm conversions and increases in production in this region have been in part attributed to developments in irrigation technology, which provides access to underground and stored water sources (Pangborn et al., 2016). In addition to the irrigation of arid land, increased use of synthetic fertilisers has supported the rapid expansion and intensification of dairy farming in Canterbury (and elsewhere in New Zealand).

Key challenges associated with the use of synthetic fertilisers include the leaching of excess nutrients into waterways, particularly nitrogen and phosphorus, leading to environmental degradation (e.g., Larned et al., 2016). Concerns about environmental impacts, particularly the deterioration of New Zealand's freshwater ecosystems, have led to regulations by central and local government authorities aimed at limiting nutrient loss from agricultural land (Ministry for the Environment, 2023).

One of the tools widely used in New Zealand to estimate nutrient flows in agricultural and horticultural farming systems is the model OVERSEER® (hereafter called "OverseerFM") (Freeman et al., 2016; Pinxterhuis & Edwards, 2018; Watkins & Selbie, 2015). The model can be used to generate predictive nutrient budget analyses and to derive estimates of potential nutrient loss, documenting the inputs and outputs to a given scale (e.g., block or farm). As such, the model supports on-farm decision-making pertaining to nutrient management and farming practices. In addition, the OverseerFM software has been used to calculate estimates of nutrient loss (via surface run-off and leaching) and greenhouse gas emissions, allowing for the identification of potential environmental risks (Monaghan et al., 2021). Underlying assumptions inherent in the use of OverseerFM software are that the farm management systems are unchanging and apply "good management practices", and that inputs into the model are "reasonable" and accurate (Reisinger et al., 2017).

Nutrient budget analyses generated by OverseerFM have also been used in a regulatory setting, as regional councils are required to monitor nutrient loads and sources to assess potential impacts on water quality. A recent review of OverseerFM by the Parliamentary Commissioner for the Environment raised concerns about its use by regulators, but highlighted its value as a nutrient budget analysis tool (Parliamentary Commissioner for the Environment, 2018; and see government response by Ministry for the Environment and Ministry for Primary Industries, 2021).

Notwithstanding the limitations of OverseerFM outlined in the review, its widespread use as a nutrient budget analysis tool has resulted in a comprehensive dataset of New Zealand dairy farm systems. These data provide information on nutrient loss, such as nitrogen, including changes over time.

This report presents a review and characterisation of OverseerFM data from dairy farm systems in the Canterbury region, with a focus on nitrogen loss. The current data collation was based on nutrient budget analyses generated by OverseerFM, made available by Overseer Limited.

2. METHODS

Nutrient budget analyses were made available by Overseer Limited from the database supporting the OverseerFM software platform. In addition, the present review included information from analyses provided to Environment Canterbury and other parties (e.g., irrigation scheme managers, fertiliser companies).

OverseerFM nutrient budget analyses are prepared by farmers and their advisors to help manage agricultural enterprises such as dairy herds, cropping land, or sheep and beef production. The analyses support best-practice decisions around many aspects of agricultural practice, including fertiliser use, irrigation, and stocking numbers.

The current study was focused on nutrient budget analyses that include dairy enterprises. These enterprises are comprised of dairy or dairy replacement enterprise types. In particular, dairy grazing enterprises were not included here.

Budgets are prepared for farms using the OverseerFM web-based tool. When these budgets are saved, an OverseerFM analysis is performed, which includes a validation of inputs, and produces estimates of nitrogen lost to the environment from the farm (i.e., nitrogen loss, defined as nitrogen leaving the farm through processes such as run-off and leaching). If the budget is consistent, an analysis summary is produced for the farm. The dataset for the present study was limited to budgets that succeeded in producing an analysis summary.

Within OverseerFM, each budget analysis is associated with a farm located in one of the OverseerFM-designated regions, corresponding with climatic regions. For this study, only budget analyses that were indicated to be from the Canterbury region were selected. It is worth noting that the Canterbury region in OverseerFM is not an exact match with the region covered by Environment Canterbury Regional Council. Nevertheless, the overlap between the two regions was considered sufficient for the purpose of this study.

An OverseerFM farm nutrient budget analysis includes details describing a dairy farm enterprise, such as the number of animals and total milk production. These data were characterised in the present study to gain an understanding of the proportion of Canterbury dairy farms included in the analyses, and to identify trends in nitrogen loss over time.

2.1 Initial data exploration

The OverseerFM database was provided on 22 May 2023, version 6.5.1. The present study dataset was created from those records using a number of filters and preparation rules.

OverseerFM budget analyses can be prepared to report on typical farm activity over a farm year. These analyses are recorded in the database as year-end and represent a farm's activity from 1 July to 30 June the following year, with the latter indicating the reporting year used here. For example, a year-end analysis for 2021 covers the period from 1 July 2020 to 30 June 2021. Also used here is the notation 2020–21 for a year-end 2021 budget analysis. The initial data exploration included the 12-year period period for the farm years 2011 (July 2010 to June 2011) to 2022 (July 2021 to June 2022).

Within this period, over 98% of the budget analyses in the OverseerFM database were marked as year-end analyses (Table 1). Over the reporting period, a considerable number of the year-end budget analyses for all of New Zealand were from the Canterbury region, and the latter were largely from dairy enterprises. For example, for the 2022 farm year, 69% of budget analyses from Canterbury included dairy enterprises.

Table 1: Number of nutrient budget analyses in the OverseerFM database for farm years between 2010–11 and 2021–22. Records shown are the number of nutrient budget analyses prepared in each farm year. Shown are all nutrient budget analyses from New Zealand (NZ), all year-end analyses and year-end analyses for dairy enterprises for all of New Zealand, and for the Canterbury region only.

Year	NZ	NZ year-end		Canterbury year-end	
	No. all	No. all	No. dairy	No. all	No. dairy
2010–11	631	629	249	614	243
2011–12	658	655	266	628	250
2012–13	1 292	1 287	587	1 125	440
2013–14	495	495	384	253	159
2014–15	870	867	650	320	227
2015–16	1 520	1 508	1 046	769	520
2016–17	2 313	2 274	1 741	1 022	706
2017–18	3 240	3 141	2 328	1 319	822
2018–19	3 822	3 776	2 610	1 420	822
2019–20	4 482	4 415	2 930	1 579	883
2020–21	3 709	3 679	2 474	1 151	729
2021–22	3 566	3 411	2 598	996	685
Total	26 598	26 137	17 863	11 196	6 486

In addition to year-end budget analyses that are prepared each year, a number of year-end budget analyses are also carried forward from previous years. Typically, OverseerFM year-end budget analyses are not prepared every year for every farm, unless there are marked changes in farm characteristics or management practices, and existing nutrient budget analyses no longer represent the existing farming system (A. Taylor, Overseer Ltd., pers. comm.). For example, a budget analysis is carried forward for a farm that has a nutrient budget analysis for 2019–20, but not for 2020–21 or 2021–22, so that the information from the 2019–20 analysis is carried forward and used for the subsequent farming years (in this example, for 2020–21 and 2021–22). The practice of carrying nutrient budget analyses forward meant that the OverseerFM dataset for the period between 2011 and 2022 included a combination of year-end analyses that were carried forward from previous years, in addition to year-end analyses that were prepared each year (Table 2). For example, for the most recent farming year (2022), the total number of 1192 year-end budget analyses included 685 analyses that were prepared in 2022, with the remaining number of records representing nutrient budget analyses that were prepared in previous years. The carried-forward budgets were included in the study dataset, but were not used to fit the statistical model to analyse nitrogen loss (see Section 2.5).

Table 2: Number of nutrient budget analyses from Canterbury dairy farms recorded in OverseerFM for the period between 2010−11 and 2021−22. Shown are the total number of records for each farming year, and the number of records by year, identifying the number of year - end analyses that were carried forward from previous years. Records highlighted in grey were year - end analyses carried forward from earlier years and not included in the current study dataset.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
2011	243												243
2012	17	250											267
2013	7	9	440										456
2014	6	7	336	159									508
2015	6	5	296	42	227								576
2016	4	3	202	25	61	520							815
2017	4	2	119	16	32	131	706						1 006
2018	4	1	65	11	21	53	124	822					1 096
2019	3	1	39	6	16	29	73	193	822				1 139
2020	1	1	26	4	12	18	38	88	142	883			1 181
2021		1	22	3	11	16	28	69	76	284	729		1 202
2022		1	21	3	11	16	26	53	57	196	175	685	1 192

2.2 Study dataset

For the current analysis, the period for nutrient budget analyses carried forward was limited to the period from 2017 onwards. For example, a nutrient budget analysis that was prepared in 2012–13 and subsequently carried forward each year to 2016–17 was included in the current dataset.

Limiting the study data set to nutrient budget analyses for the farm years 2016–17 to 2021–22 included the period when the total number of analyses exceeded 1000 analyses in each year (see Table 2). There was a steady increase in the number of analyses over this period, and over half of the analyses in each farm year were prepared for that year (Figure 1).

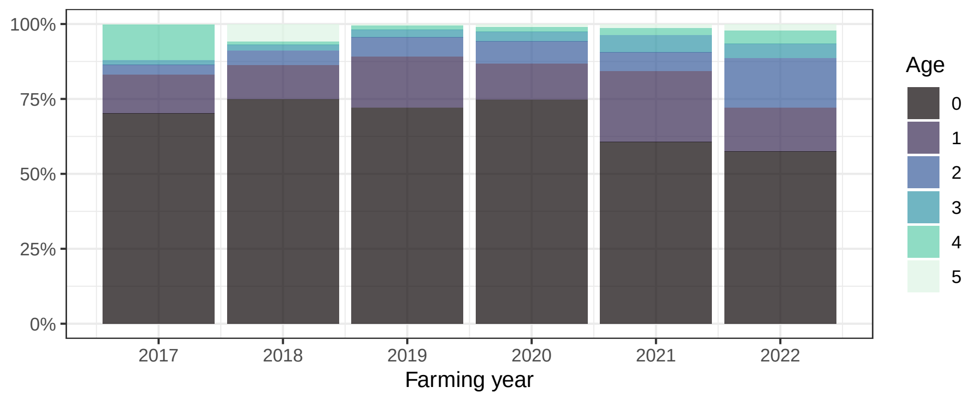

Figure 1: Composition (%) of the ages of nutrient budget analyses included in the current study dataset of Canterbury dairy enterprises. Colour indicates the age of the analyses carried forward in years.

2.3 Geographical distribution

The size of the Canterbury region is over 4.5 million hectares, making it the largest region in New Zealand. To provide a more detailed analysis, the Canterbury region was split into six sub-regions that divided the dairy farming areas relatively equally, and represented naturally-defined areas (Figure 2). The first split was between "hill country" and plains based on a measure of steepness as recorded in the New Zealand Land Resource Inventory. Subsequently, the plains were further divided into five sub-regions, defined by main rivers; these sub-regions were (north to south): Waimakariri, Selwyn, Ashburton, Rangitata, and South Canterbury. The names for these sub-regions corresponded with the spatial division applied here (but not with names for district council areas).

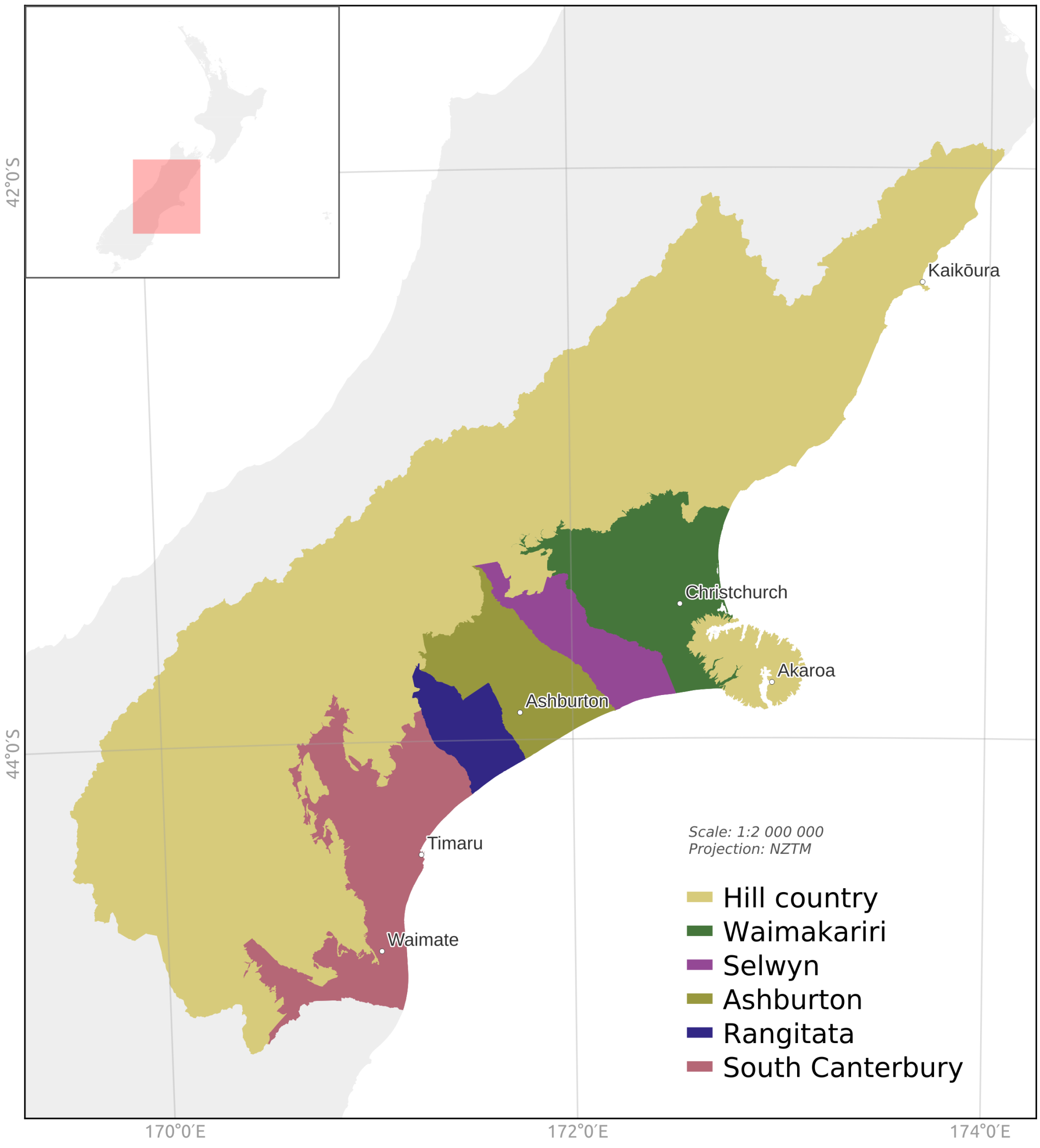

Figure 2: Spatial division of the Canterbury region into six sub-regions used in the present study. The sub-regions represent similar dairy farming areas, dividing the "hill country" from the plains (at 300 m altitude), with five further divisions of the plains by main rivers. Place names included for reference.

The OverseerFM platform allows geographical shape files (geographical information system, GIS) to be loaded; however, these files are not a requirement, and only few farms have this type of information. To identify the location of farms from the budget analysis data, we used spatial information where possible, such as the default climate latitude and longitude. Using this approach, the location of most farms was identified; however, for an average of 0.46% of Canterbury dairy farms each year the sub-region could not be ascertained for the current dataset. An example of the number of farms and dairy farms in 2020–21 illustrated the characteristics of the Canterbury sub-regions, which were aimed to be naturally defined while representing similar dairy farm numbers and areas (Table 3).

Table 3: Canterbury sub-regions, as defined in the current study, including their size, and the total number and size of all farms and of dairy farms included in the OverseerFM database for 2020–21. Data include nutrient budget analyses for farming year 2020–21. Farms without spatial information were included under "not located".

Sub-region	Area (ha)	All farms		Dairy farms	
		No.	Area (ha)	No.	Area (ha)
Hill country	3 307 406	339	398 011	124	39 226
Waimakariri	321 887	456	78 274	191	41 067
Selwyn	144 628	291	57 523	172	43 016
Ashburton	222 386	564	81 141	225	57 088
Rangitata	106 439	335	63 992	198	48 352
South Canterbury	417 888	528	156 728	287	73 169
Not located		15	2 465	5	752
Canterbury	4 520 634	2 528	838 134	1 202	302 672

2.4 Canterbury dairy farms in OverseerFM

The current characterisation of the OverseerFM budget analyses included a summary of the total number of Canterbury dairy enterprises in the database. To estimate this coverage, three metrics for dairy enterprises were used in the current analysis: the land area covered, the size of the dairy herd (as stocking rate), and the total milk production (as kg solids). Each of these metrics were defined from data in the OverseerFM nutrient budget analyses (see the distribution of these data in Appendix A, Figures A-1 to A-3), and then compared with independently-published numbers characterising the size of the Canterbury dairy industry.

For land area covered, information within OverseerFM distinguishes a farm by blocks of different types, which are associated with different enterprises. To estimate the productive size of a farm in hectares, areas for productive blocks were combined for farms that had a dairy enterprise (see data summary in Table 4). The productive area is the sum of the areas of productive pasture and fodder crops. Typically, the area of a farm may be larger, as it may include forestry, cropping, or other land uses that were not part of the present study.

Another metric for characterising a dairy enterprise is the size of a dairy herd or the stocking rate. As the number of animals on a farm changes over the course of a year, farm nutrient budget analyses are defined in terms of animal events, when animals are either introduced to the farm or removed. These data are then converted into "mobs" in

Table 4: Comparison of farm area definitions for OverseerFM Canterbury budget analyses from 2016–17 to 2021–22. Total: total farm area defined independently of blocks; blocks: sum of the area of all blocks; productive blocks: sum of the area of productive blocks; productive area: sum of blocks with type productive pasture or fodder crops.

Year	No. farms	Canterbury farm area, ha			
		Total	Blocks	Productive blocks	Productive area
2016–17	1 006	269 604	263 650	253 332	250 927
2017–18	1 096	305 964	297 906	285 996	280 815
2018–19	1 139	324 211	314 637	302 794	294 844
2019–20	1 181	335 925	324 205	313 693	299 584
2020–21	1 202	342 994	330 586	320 468	302 672
2021–22	1 192	339 331	325 917	317 590	297 472

the OverseerFM model, defined by animal category, breed, sex, and monthly count. To provide a standard measure for animals on a farm, these data are converted to a stocking rate, defined as revised stock unit (RSU). The RSU is based on animal intake of energy, defined in OverseerFM as 6000 megajoules of metabolisable energy (MJ ME) per year, and deemed similar to a standard stock unit (OverseerFM, 2018). The corresponding stocking rate for a farm is "estimated as total RSU divided by total farm area", i.e., RSU/ha.

The OverseerFM budget analyses also include details about the milk production of a herd or farm, measured in kilogrammes of milk solids. The budget analyses provide a total for this metric, which represents another measure for characterising a dairy farm.

For the comparison of OverseerFM records with other data sources, a previous analysis of rural land use (and nitrate losses) in Canterbury highlighted the lack of a single authoritative source of information of rural land use in New Zealand that is accurate and comprehensive (Hill & Ford, 2015). This shortfall makes comparisons between different databases difficult. In addition, there may be differences in the metrics used or how they are defined in each database. For example, annual reports of dairy farming present the total number of cows milked (e.g., Livestock Improvement Corporation Limited and DairyNZ Limited, 2021), whereas StatsNZ reports the total number of dairy cattle, which includes several categories of dairy cattle such as dairy bulls, calves, and cows and heifers that are not in milk production (see data at StatsNZ, 2023).

Used in the comparison here were records from the annual reports of dairy farming in New Zealand (hereafter called "DairyNZ" records; Livestock Improvement Corporation Limited and DairyNZ Limited, 2017, 2018, 2019, 2020, 2021, 2022), because these records were considered to be the most accurate information in a previous comparison of data sources (Hill & Ford, 2015). DairyNZ records distinguish information for North and South Canterbury, and exclude the Waitaki district. North Canterbury includes the districts Hurunui, Waimakariri, Christchurch City, Banks Peninsula, Selwyn, and Ashburton; South Canterbury includes Timaru, Mackenzie, and Waimate. The comparison here combined the numbers provided by DairyNZ to obtain total numbers for the Canterbury region.

2.5 Statistical analysis of trends in nitrogen loss

The development of a model to analyse nitrogen loss considered the parameterisation of three models initially (see Table B-1). All three models included penalised splines to derive the statistical strength of annual and geographical trends. The differences between the models related to the way the size of farms was included in each of them.

In model A, the size of the farms was included by including herd size (RSU) and productive area (through stocking rate, RSU/ha) as independent variables. In model B the dependent variable was nitrogen loss per ha, and did not include the herd size or area as independent variables. In comparison, model C estimated total nitrogen loss similar to model A, but included offsets for herd size and area.

The predicted annual change in nitrogen loss was calculated for each of the three models (Table B-2). The predictions from the three models showed considerably overlap, with the mean annual rate varying between -6.1% and -5.2%. (Note that for model B, the credible interval included 0, indicating that the model did not exclude the possibility of no overall change, although it was unlikely). Models A and B predicted similar year and sub-region effects (Figure B-2), whereas Model C predicted different sub-regional effects. Model C also had unbalanced residuals, indicating that it was not fitting the data adequately well (Figure B-3c).

Based on this parameterisation, model A was selected for the analysis, because it had the best fit to the data (Figure B-1) and balanced residuals (Figure B-3). The model also controlled for marked changes in the size of farms over the period.

To analyse trends, a generalised linear model (GLM) was fit to the data of nitrogen loss, with independent variables productive area (ha), stock numbers (RSU), year, and sub-region (Table 5). The data of nitrogen loss had a log-normal distribution. The R package "brms" (Bürkner, 2017) was used to implement the model. This package provides an efficient interface for fitting GLMs in the Stan language for Bayesian statistics (Carpenter et al., 2017). The model was fit with four separate sets of Markov chain Monte Carlo (MCMC) samples, with 2 000 warm up iterations, and 4 000 samples in each set. This approach produced a total of 16 000 samples from the posterior probability distribution (see Appendix B, Figure B-4 for parameter distributions and the traces of the MCMC chains, and Table B-3 for the mean, median and quantile ranges for the fit model parameters).

In the model, the total stock number and stocking rate (RSU/ha) were transformed by a logarithm. The total size of the farm was included as the stocking rate. These two independent variables were combined to describe the size of the farm.

The model did not attempt to explain the internal OverseerFM model that estimates nitrogen loss for a farm, but was focused on assessing trends that are evident in the data. For this reason, the model was simple and used only stocking rate and total stock number (RSU) as the main independent variables for total nitrogen loss. The OverseerFM model uses a number of other factors to calculate the nitrogen loss from a farm, and these additional factors were not used in the current model. For example, fertiliser use is one of the factors that is included in the OverseerFM data and expected to be correlated with changes in nitrogen loss. Nevertheless, the model here was aimed at quantifying the trends in nitrogen loss, without attempting to explain the causes of any change.

The farm intensity numbers, productive area and stock numbers, needed to be accounted for to gain an understanding of temporal or spatial trends. The model derived estimates

Table 5: Definition of the statistical model to assess nitrogen loss, using the BRMS package (Bürkner, 2017).

Model aspect	Definition
`n_loss ~ I(log(rsu)) + I(log(stock_rate)) + t2(sub_region,year, bs=c('re', 'cr'))`	Formula
`n_loss`	Total nitrogen loss (kg) for a farm.
`I(log(RSU))`	Total number of stock on a farm (revised stock unit, RSU), transformed by the logarithm.
`I(log(stock_rate))`	Stocking rate on a farm (RSU/ha), transformed by the logarithm.
`t2(sub_region,year, bs=c('re', 'cr'))`	Penalised cubic spline of year effect, with random effect parametrised by sub-regions.

for the strength of annual trends and differences between the sub-regions after taking into account the farm area and stock numbers.

The model was fit to year-end nutrient budget analyses for the farming years 2016–17 to 2021–22 that describe Canterbury dairy farms, and omitting the carried-forward budget analyses. The dataset included 4634 records, and included 68% of the data with carried-forward analyses. There were a mean number of 129 farms in each of the sub-region/year strata (see Table 6).

Table 6: Number of Canterbury dairy farms and total nitrogen loss (N_{loss}, millions kg) by year and sub-region in the dataset used to fit the current model for assessing nitrogen loss.

Sub-region	2016–17		2017–18		2018–19		2019–20		2020–21		2021–22	
	No. farms	N_{loss}	No. farms	N_{loss}	No. farms	N_{loss}	No. farms	N_{loss}	No. farms	N_{loss}	No. farms	N_{loss}
Hill country	87	1.33	96	1.38	97	1.39	98	1.41	67	0.85	57	0.69
Waimakariri	99	1.33	106	1.33	145	1.83	143	1.70	121	1.44	114	1.18
Selwyn	102	1.67	116	1.71	129	1.89	128	1.67	120	1.52	112	1.22
Ashburton	136	2.38	163	2.72	156	2.45	157	2.23	134	1.81	121	1.50
Rangitata	129	2.34	154	2.90	132	2.32	137	2.26	110	1.63	112	1.48
South Cant.	150	1.93	185	2.39	161	2.09	218	2.63	175	2.01	167	1.68

3. RESULTS

The OverseerFM nutrient budget analyses provided a detailed description of Canterbury dairy farms. The use of OverseerFM has steadily increased since 2010–11, and since 2016–17, a total of 1269 dairy farms have had budget analyses prepared for them. Since 2018–19, over 90% of the dairy farms were represented in each of the four most recent years (see Table 1).

3.1 Comparison with dairy farm records from other sources

Comparing data from OverseerFM nutrient budget analyses with records from DairyNZ (Livestock Improvement Corporation Limited and DairyNZ Limited, 2017, 2018, 2019, 2020, 2021, 2022) documented relatively similar numbers for dairy farm metrics overall, particularly in recent years (Table 7). Some of the higher numbers in the OverseerFM analyses compared with DairyNZ records may be linked to the latter excluding the Waitaki district.

For number of dairy farms, "number of herds" recorded by DairyNZ were used as a proxy for comparison with the "number of farms with a dairy enterprise" in OverseerFM, noting that some farms have more than one herd. Numbers from both sources were similar, with OverseerFM including slightly more dairy farms than DairyNZ in the two most recent years.

Similarly, milk production numbers were similar between the two data sources, with OverseerFM data representing a higher production number than DairyNZ records for most years.

The comparison of dairy farm or productive area used records of "effective area" from DairyNZ records, which excludes the milking platform and support block (e.g., see Livestock Improvement Corporation Limited and DairyNZ Limited, 2022), whereas this area is included in OverseerFM. This difference in the area definition between the two data sources may explain the higher values for productive area (defined as productive pasture and fodder crop blocks) in OverseerFM.

Based on this comparison, the study dataset from OverseerFM was considered to provide a comprehensive representation of Canterbury dairy farms.

Table 7: Comparison of Canterbury dairy farms between records included in the study dataset of OverseerFM nutrient budget analyses (OFM) and by the Lifestock Improvement Corporation and DairyNZ (DNZ). Percentage values indicate the difference of OFM to DairyNZ records that were considered to represent the total (100%) of records. The number of dairy farms is reported as "number of herds" by DairyNZ, and productive area is reported as "effective area" (excluding the milking platform and support block).

Year	Number of dairy farms			Milk solids, million kg			Productive area, ha		
	OFM	DNZ	%	OFM	DNZ	%	OFM	DNZ	%
2016–17	1 006	1 184	85	348	386	90	250 927	271 102	93
2017–18	1 096	1 191	92	381	388	98	280 815	277 158	101
2018–19	1 139	1 200	95	410	405	101	294 844	279 203	106
2019–20	1 181	1 201	98	431	419	103	299 584	280 458	107
2020–21	1 202	1 198	100	443	423	105	302 672	280 435	108
2021–22	1 192	1 189	100	435	406	107	297 472	279 765	106

3.2 Canterbury dairy farms in the OverseerFM study dataset

Canterbury dairy farms included in the OverseerFM study data set were characterised by their productive area (hectares), herd size (as RSU), and milk production (see the distribution of these data in Appendix A, Figures A-1 to A-3).

Considering the size of the dairy industry by area, Canterbury dairy farms included in the OverseerFM database represented a maximum of 302,672 hectares of productive land in this region in 2020–21 (see Appendix A, Table A-1). This area represented 7% of the total land area of the Canterbury region, and 25% of the Canterbury plains.

Across sub-regions, the total area of productive dairy land decreased in recent farm years, between 2020–21 and 2021–22, in the Waimakariri, Selwyn, and Ashburton sub-regions, compared with a moderate increase in South Canterbury.

The dairy stock on Canterbury dairy farms peaked in 2020–21 at 9,926,108 RSU, and the total corresponding stocking rate reached 31 RSU/ha. Over the entire period of the study dataset, the stocking rate decreased by 1% (Table 8). There was little change in the number of dairy stock per farm, which had a mean of 8 096 RSU per farm.

Table 8: Annual dairy stock numbers for Canterbury farms, for dairy and dairy replacement enterprises. Stocking rate (revised stock unit, RSU) per hectare was based on the productive area, and the herd size was calculated per farm.

Year	No. farms	Stock numbers, RSU		Stocking rate	Herd size
		Dairy	Replacement	RSU/ha	RSU/farm
2016–17	1 006	7 703 665	173 659	31.1	7 830
2017–18	1 096	8 486 762	216 467	30.4	7 941
2018–19	1 139	9 030 057	228 568	30.6	8 129
2019–20	1 181	9 444 716	233 163	30.9	8 195
2020–21	1 202	9 687 245	238 862	31.0	8 258
2021–22	1 192	9 565 665	236 122	30.9	8 223

3.3 Nitrogen loss

The dataset included an estimate of the total nitrogen loss derived from the OverseerFM model for each farm. Nitrogen loss is reported in OverseerFM as a rate per hectare, based on the total farm size, in kg/ha/yr. The total farm size may include non-dairy related land, so that the current reporting includes nitrogen loss per hectare based on productive area.

Total nitrogen loss decreased by 9.16% over the six years of the study dataset, to 14.59 million kg in 2021–22. This decrease corresponded with a 27.57% decrease of mean nitrogen kg per hectare (Table 9).

Across the different sub-regions defined in this study, there was considerable variation in nitrogen loss (Figure 3). Dairy farms in the Rangitata sub-region had the highest mean rate of nitrogen loss per hectare of the six sub-regions, followed by dairy farms in the Ashburton sub-region (Figure 3). Dairy farms in the other four sub-regions, hill country (>300 m altitude), Waimakariri, Selwyn, and South Canterbury sub-regions, all had a mean rate of nitrogen loss of approximately 40 kg per hectare.

Table 9: Annual nitrogen loss for Canterbury dairy farms from 2016–17 to 2021–22, reported as total nitrogen (kg), and as mean and median kg per hectare. Mean and median values are presented by productive area and the total area of farms.

Year	No. farms	Total N, kg	Productive area, kg/ha		Total area, kg/ha	
			Mean	Median	Mean	Median
2016–17	1 006	16 065 146	63.8	58.2	60.0	55.0
2017–18	1 096	16 897 620	60.1	56.1	56.5	52.3
2018–19	1 139	16 856 859	56.6	51.6	53.3	49.1
2019–20	1 181	16 302 831	52.7	48.6	49.6	46.2
2020–21	1 202	15 670 785	49.4	45.2	46.5	42.7
2021–22	1 192	14 593 292	46.2	42.4	43.4	40.2

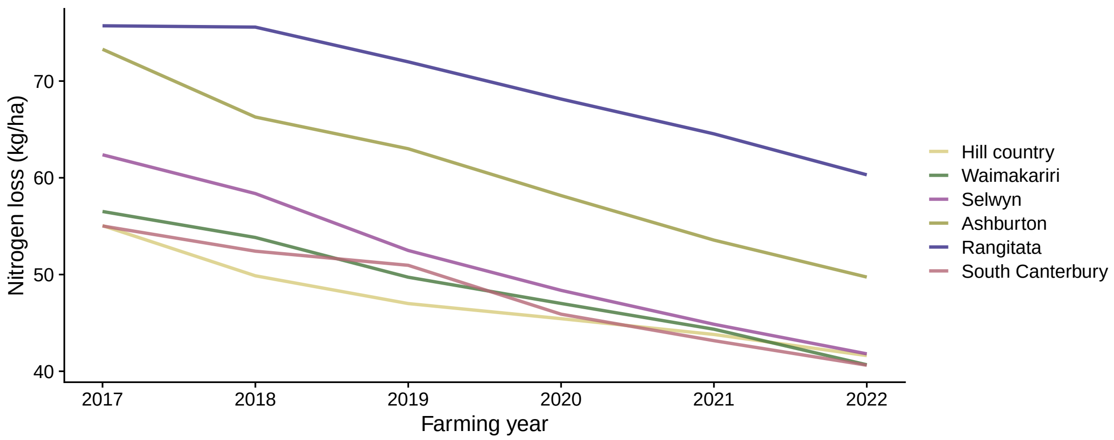

Figure 3: Mean nitrogen loss (kg) per hectare of productive farm area for Canterbury dairy farms, for each of the six sub-regions as defined in this study. The sub-regions were defined as hill country at >300 m altitude, with five further divisions of the plains, defined by main rivers.

3.4 Modelled trends in nitrogen loss

The statistical model fit six parameters to the study dataset using four MCMC chains. The densities and traces of the model fit showed that the model was well defined and converged (Appendix B, Figure B-4). The log-normal distribution of nitrogen loss was defined by the intercept (mean 0.435) and sigma (mean 0.495) parameters (Table B-3). The log-normal distribution was strictly positive. The penalised cubic splines for the sub-region/year random effects were controlled by the two SD (standard deviation) hyper-parameters. The values of these estimated parameters showed that the model predicted more variability between years than between sub-regions (see Table B-3).

The model can be used to predict on the full study dataset that included carried-forward budget analyses. Comparing the predictions across a grid of productive area and stock number deciles revealed that the model accurately replicated the effect that nitrogen loss increased with both farm size and stock numbers (Figure B-1). Comparison of the predicted estimates for each year and sub-region with the total nitrogen loss estimated by the OverseerFM model showed that the model captured the signal of total nitrogen loss (Figure B-5).

The stocking rate parameter was estimated to be negative, suggesting that increasing the stocking rate (RSU/ha) while holding the stock number (RSU) constant reduced the total nitrogen loss. The RSU parameter was slightly less than one, indicating that the total nitrogen loss closely followed the total stock number. These two parameters characterised how nitrogen loss depended on the size of a farm: nitrogen loss was mostly determined by the stock number, but was negatively correlated with the stocking rate (Figure 4).

The sub-region effect identified the Rangitata sub-region as having the highest nitrogen loss, followed by the Ashburton sub-region (Figure 4). In comparison, the Waimakariri, Selwyn, and hill country sub-regions were similar. The South Canterbury sub-region had the smallest effect, even though this sub-region had the highest total nitrogen loss in 2021–22 (see Figure A-5).

The model provided estimates of trends in nitrogen loss after taking account of the size of dairy farms in terms of herd size and productive area. These trends were compared in terms of relative change by sub-region and year. All sub-regions had decreasing nitrogen loss over the six-year period (Figure 5, Table 10). For the entire Canterbury region, the OverseerFM data reported a decrease in nitrogen loss of -5.7% per year for the six years from 2016–17 to 2021–22. The Waimakariri sub-region had the smallest reduction of -3.7%, whereas the Ashburton sub-region showed the largest reduction of -6.6% nitrogen loss.

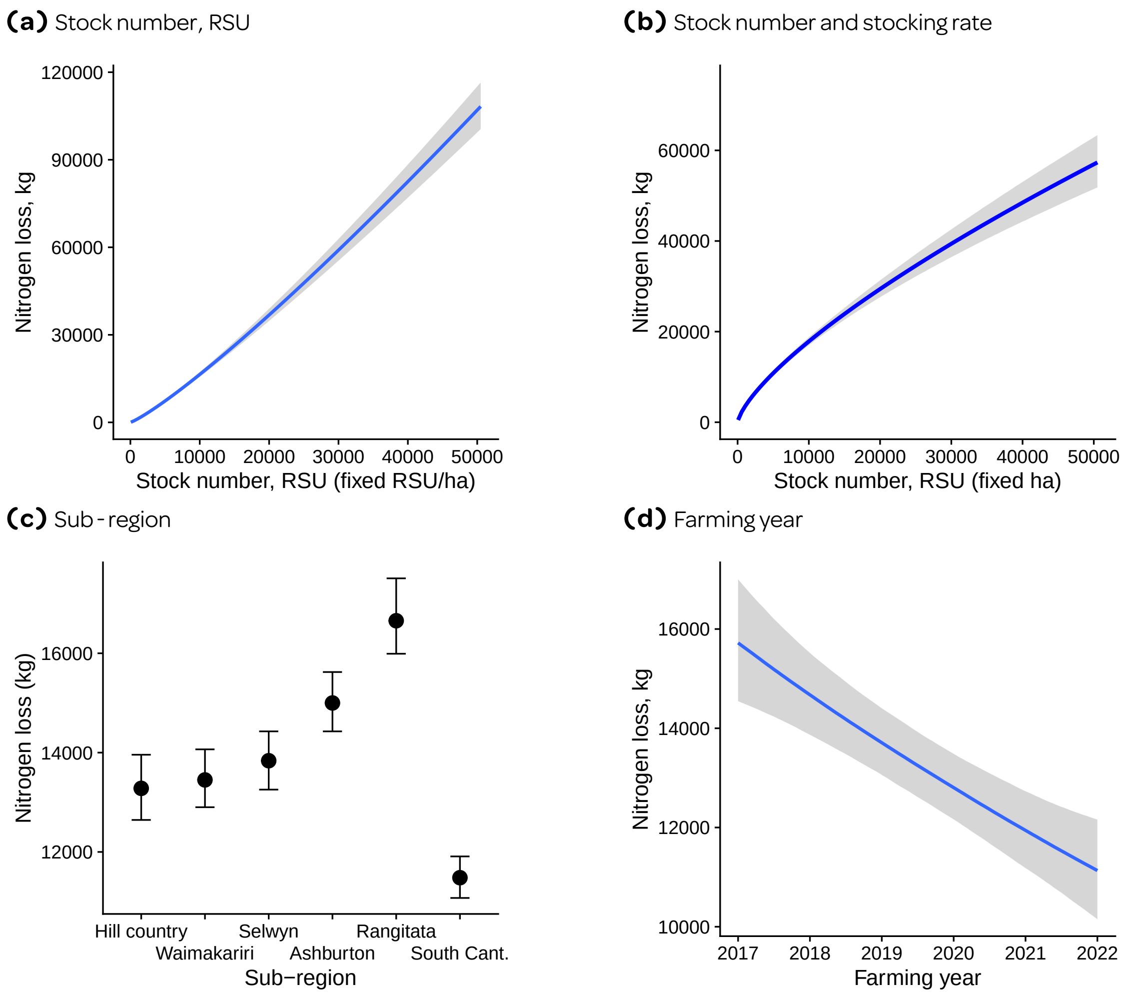

Figure 4: Conditional effects for stock number (revised stock unit, RSU), stock number and stocking rate (productive area set to 320 ha), sub-region, and year. The plots show the strength of the effects conditioned on all other model effects being held constant. Stocking rate, stock number, and year are conditioned to the input data mean, and the sub-region is conditioned to the hill-country reference region. (Note different scales on y-axes.)

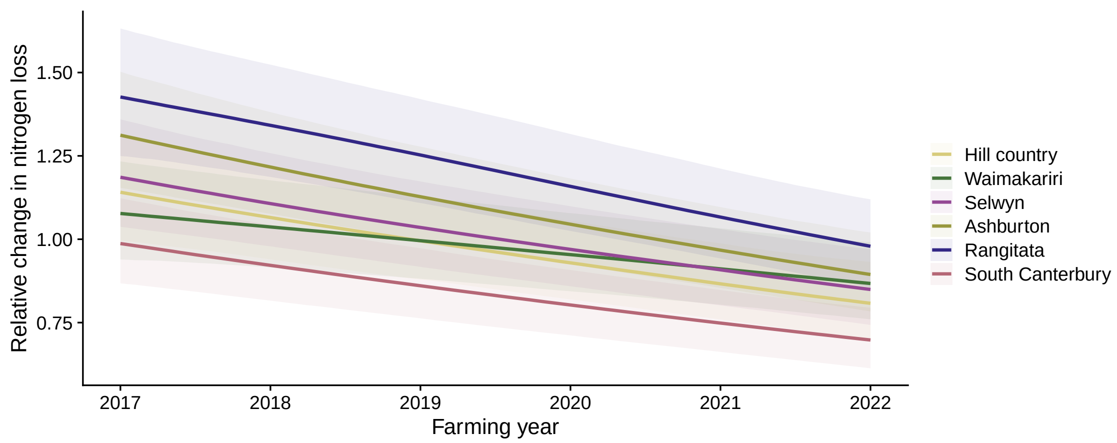

Figure 5: Modelled effect of year and sub-region, holding the stock number (revised stocking unit, RSU) and farm size (ha) fixed. Shading indicates 95% credible interval.

Table 10: Annual change (%) in total nitrogen loss over six years from 2016–17 to 2021–22, estimated by the statistical model. Percentages are shown for each sub-region and the entire Canterbury region.

Sub-region	Year effect		Change, %		
	Start	End	Mean	Lower	Upper
Hill country	1.14	0.81	-5.92	-1.12	-11.06
Waimakariri	1.08	0.87	-3.68	0.89	-8.41
Selwyn	1.19	0.85	-5.72	-1.12	-10.60
Ashburton	1.31	0.89	-6.60	-2.07	-11.46
Rangitata	1.43	0.98	-6.48	-1.84	-11.37
South Canterbury	0.99	0.70	-5.95	-1.48	-10.62
Canterbury	1.19	0.85	-5.72	-1.12	-10.59

4. DISCUSSION

The current study of OverseerFM data included a characterisation of Canterbury dairy farms and associated nitrogen loss for the period from 2016–17 to 2021–22. Using dairy farm metrics reported by DairyNZ provided a comparison of OverseerFM data with independently-reported measures of farm size, geographical area, and total milk production. This comparison showed that the OverseerFM database had a comprehensive record of Canterbury dairy farms for the study period. Within this period, the OverseerFM data included over 1000 nutrient budget analyses each year.

The OverseerFM input data for the nutrient budget analyses are self-reported, and typically prepared by farm advisors for the farmer (or for other stakeholders). The study dataset included nutrient budget analyses that were generated by the OverseerFM model, which included a number of validation steps. In the OverseerFM model, nutrient budget analyses are excluded if the model is unable to balance the overall nutrients. For example, if the production is impossible from the stock rate, or there are inadequate inputs to support the stock. Environment Canterbury Regional Council has required dairy farms to use OverseerFM to produce nutrient budget analyses, and that the nutrient budget analyses are assessed by an authorised auditor. This requirement has resulted in a comprehensive dataset of nutrient budget analyses that is representative of Canterbury dairy farms and almost complete for this region.

A statistical model was fit to the OverseerFM nutrient budget analysis data to assess annual trends in estimated nitrogen loss. The model incorporated two independent variables that control the scale of nitrogen loss on farms: stock number and farm size. The farm size was included via a stocking rate effect, indicating stock density of a farm. Having controlled for farm size, the model used a penalised cubic spline, parametrised over sub-regions, to identify trends that remained in the data. These trends showed the effect of farm system changes that are captured by the OverseerFM model.

Based on this modelling, nitrogen loss from Canterbury dairy farms was decreasing over the study period at an annual rate of 5.7% (95% c.i.: 1.1% to 10.6%) per year, or 29.8% (95% c.i.: 6.6% to 48.9%) over six years. This decrease was estimated after the size of the Canterbury dairy industry was factored out by the model and, therefore, was not related to changes in dairy farm area or herd size over this period. The modelled decrease in nitrogen loss indicates changes in farming practice that were reported in OverseerFM nutrient budget analyses. Further analysis of OverseerFM data could be used to investigate this aspect.

The model was also designed to determine any variation between the six geographical sub-regions that were defined as part of this study. This part of the analysis showed that the Ashburton sub-region had the strongest reduction in nitrogen loss, whereas the Waimakariri sub-region had the weakest evidence of a reduction. The South Canterbury sub-region had lower nitrogen loss per hectare of productive land, after taking into account farm size, than the other regions. Nevertheless, South Canterbury reported the highest total nitrogen loss, due to the large size of this sub-region.

The model was fit to nutrient budget analyses that were not carried forward, as the model aimed to determine temporal and spatial trends in the data. It was based on the assumption that analyses carried forward reflected farms that had no change in the overall farm scale or system. This approach meant that the model used here was fit to a sample of approximately 60% of Canterbury nutrient budget analyses. Although this percentage was considered a representative sample, it is possible that more frequently-updated nutrient budget analyses would refine the accuracy of the reported trends.

5. ACKNOWLEDGEMENTS

This project was supported by Overseer Limited, and access to the OverseerFM data was provided by the Overseer Limited team.

Particular thanks to Alastair Taylorm, Jean-Paul Tavernet, Mark-John Bruwer, and Jill Gower (Overseer Limited), Vera Power (Fertiliser Association of New Zealand), and Ants Roberts (Ravensdown) for feedback on the manuscript.

6. REFERENCES

Bürkner, P.-C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, *80*, 1–28. https://doi.org/10.18637/jss.v080.i01

Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M. A., Guo, J., Li, P., & Riddell, A. (2017). Stan: A probabilistic programming language. *Journal of Statistical Software*, *76*.

Freeman, M., Robson, M., Lilburne, L., McCallum-Clark, M., Cooke, A., & McNae, D. (2016). *Using OVERSEER in regulation – technical resources and guidance for the appropriate and consistent use of OVERSEER by regional councils*. Report prepared by Freeman Environmental Ltd for the OVERSEER Guidance Project Board. 130 p.

Hill, Z., & Ford, R. (2015). *Canterbury land use statistics and nitrate losses*. Memorandum. Environment Canterbury Regional Council. 18 p.

Larned, S. T., Snelder, T., Unwin, M. J., & McBride, G. B. (2016). Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research*, *50*, 389–417.

Livestock Improvement Corporation Limited and DairyNZ Limited. (2017). New Zealand dairy statistics 2016–17. https://www.dairynz.co.nz/media/5788533/nz-dairy-statistics-2016-17-web.pdf

Livestock Improvement Corporation Limited and DairyNZ Limited. (2018). New Zealand dairy statistics 2017–18. https://www.dairynz.co.nz/publications/dairy-industry/new-zealand-dairy-statistics-2017-18.pdf

Livestock Improvement Corporation Limited and DairyNZ Limited. (2019). New Zealand dairy statistics 2018–19. https://www.dairynz.co.nz/media/5792471/nz_dairy_statistics_2018-19_web_v2.pdf

Livestock Improvement Corporation Limited and DairyNZ Limited. (2020). New Zealand dairy statistics 2019–20. https://www.dairynz.co.nz/media/5794073/nz-dairy-statistics-2019-20-dnz.pdf

Livestock Improvement Corporation Limited and DairyNZ Limited. (2021). New Zealand dairy statistics 2020–21. https://www.dairynz.co.nz/media/5794941/nz-dairy-statistics-2020-21-web.pdf

Livestock Improvement Corporation Limited and DairyNZ Limited. (2022). New Zealand dairy statistics 2021–22. https://www.dairynz.co.nz/media/5796369/nz-dairy-statistics-2021-22-web.pdf

Ministry for the Environment. (2023). Synthetic fertiliser cap: Implementation guidance on essential freshwater policies and regulations. https://environment.govt.nz/acts-and-regulations/freshwater-implementation-guidance/agriculture-and-horticulture/synthetic-nitrogen-fertiliser-cap-in-place-from-1-july/

Ministry for the Environment and Ministry for Primary Industries. (2021). *Government response to the findings of the Overseer peer review report*. Ministry for the Environment and Ministry for Primary Industries, Wellington. 36 p.

Monaghan, R., Manderson, A., Basher, L., Spiekermann, R., Dymond, J., Smith, C., Muirhead, R., Burger, D., & McDowell, R. (2021). Quantifying contaminant losses to water from pastoral landuses in new zealand II. the effects of some farm mitigation actions over the past two decades [Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00288233.2021.1876741]. *New Zealand Journal of Agricultural Research*, *64*(3), 365–389. https://doi.org/10.1080/00288233.2021.1876741

OverseerFM. (2018). Overseer Knowledge base. Animal report – description of stocking rate for all enterprises report. https://support.overseer.org.nz/hc/en-us/articles/900001917046

Pangborn, M. C., & Woodford, K. B. (2011). Canterbury dairying - a study in land use change and increasing production. *New Zealand*.

Pangborn, M. C., Woodford, K. B., & Nuthall, P. L. (2016). Development of a dairy industry in a new area – land use change in canterbury, new zealand. *International Journal of Agricultural Management*, *5*(1).

Parliamentary Commissioner for the Environment. (2018). *Overseer and regulatory oversight: Models, uncertainty, and cleaning up our waterways*. Parliamentary Commissioner for the Environment. 142 p.

Pinxterhuis, I. B., & Edwards, J. P. (2018). Comparing nitrogen management on dairy farms – canterbury case studies. *Journal of New Zealand Grasslands*, 201–206. https://doi.org/10.33584/jnzg.2018.80.329

Reisinger, A., Clark, H., Journeaux, P., Clark, D., & Lambert, G. (2017). *On-farm options to reduce agricultural GHG emissions in New Zealand*. Report to the Biological Emissions Reference Group. 68 p.

StatsNZ. (2021a). Agricultural and horticultural land use (Updated 15 April 2021). https://www.stats.govt.nz/indicators/agricultural-and-horticultural-land-use

StatsNZ. (2021b). Livestock numbers (Updated 15 April 2021). https://www.stats.govt.nz/indicators/livestock-numbers

StatsNZ. (2023). Agricultural production statistics: year to June 2022 (final). https://www.stats.govt.nz/information-releases/agricultural-production-statistics-year-to-june-2022-final/

Watkins, N., & Selbie, D. (2015). *Technical description of OVERSEER for regional councils*. Report prepared for Bay of Plenty Regional Council. AgResearch RE500/.2015/084. 41 p.

APPENDIX A CANTERBURY DAIRY FARMS

A.1 Size of Canterbury dairy farms

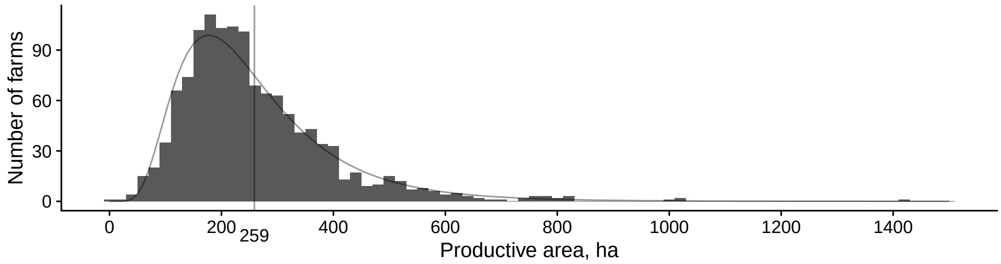

Figure A-1: Histogram (log-normal fit) of farm areas from Canterbury dairy farms that were included in OverseerFM nutrient budget analyses for farm years between 2016–17 and 2021-22. Farm sizes were grouped into 20-hectare size classes. The mean productive farm area, 258.9 hectares, is indicated with vertical line.

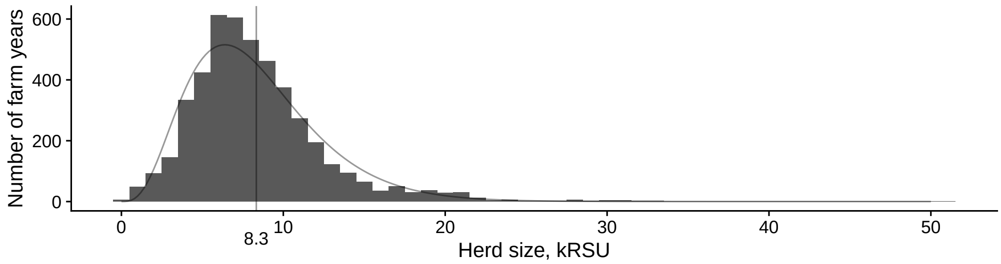

Figure A-2: Histogram (gamma fit) of farm herd size in kilo RSU (kRSU) from Canterbury dairy farms that were included in OverseerFM nutrient budget analyses for farm years between 2016–17 and 2021-22. Farm herd sizes were grouped into 1-kRSU classes. The mean value is 8.33 kRSU, indicated by a vertical line.

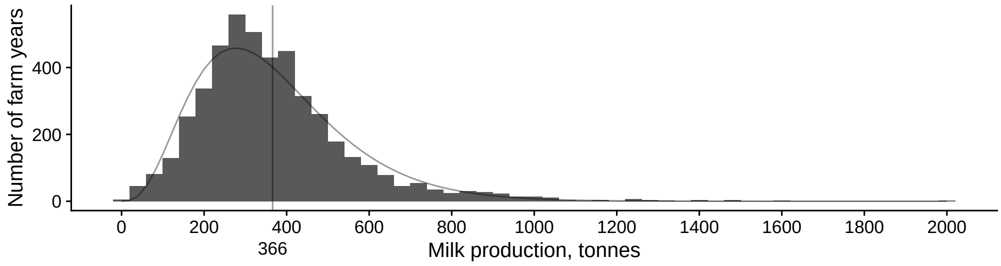

Figure A-3: Histogram (gamma fit) of farm milk production (tonnes solids) from Canterbury dairy farms that were included in OverseerFM nutrient budget analyses for farm years between 2016–17 and 2021-22. Farm milk production was grouped into 40-tonne classes. The mean value is 366.07 tonnes, indicated by a vertical line.

A.2 Land use for dairy pasture

Table A-1: Number and productive area of Canterbury dairy farms for each sub-region and total, for the period between 2017–17 and 2021–22. Not located, dairy farms without spatial information in OverseerFM.

Sub-region	2016–17		2017–18		2018–19		2019–20		2020–21		2021–22	
	No. farms	Area (ha)	No. farms	Area (ha)	No. farms	Area (ha)	No. farms	Area (ha)	No. farms	Area (ha)	No. farms	Area (ha)
Hill country	108	31 730.6	119	37 038.9	121	38 625.1	122	38 640.0	124	39 226.3	124	38 661.2
Waimakariri	147	31 702.7	164	35 238.0	183	41 334.2	190	41 427.2	191	41 067.4	187	40 116.5
Selwyn	135	34 123.6	145	36 817.2	164	41 834.6	168	43 185.6	172	43 016.1	169	41 878.4
Ashburton	199	49 082.1	214	56 071.7	216	56 701.6	223	56 004.6	225	57 088.3	224	54 720.3
Rangitata	179	44 918.1	195	48 391.0	196	48 673.0	196	48 529.3	198	48 352.5	197	48 016.1
South Canterbury	232	58 467.4	254	66 570.1	255	67 064.2	277	71 044.6	287	73 168.6	285	73 148.4
Not located	6	902.9	5	688.3	4	611.5	5	752.4	5	752.4	6	931.3
Canterbury	1 006	250 927.4	1 096	280 815.2	1 139	294 844.2	1 181	299 583.7	1 202	302 671.6	1 192	297 472.2

A.3 Nitrogen loss by sub-region

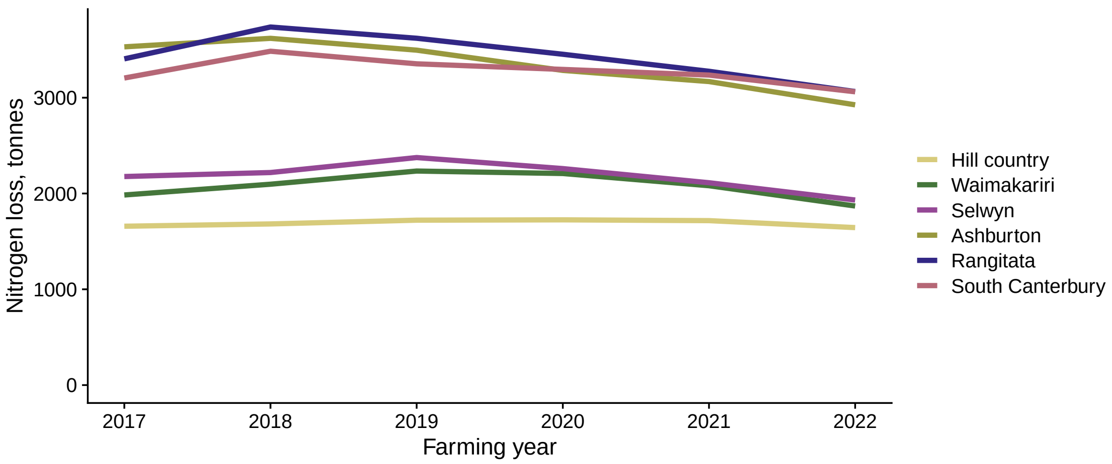

Figure A-4: Total nitrogen loss for Canterbury dairy farms, by sub-region (as defined in this study).

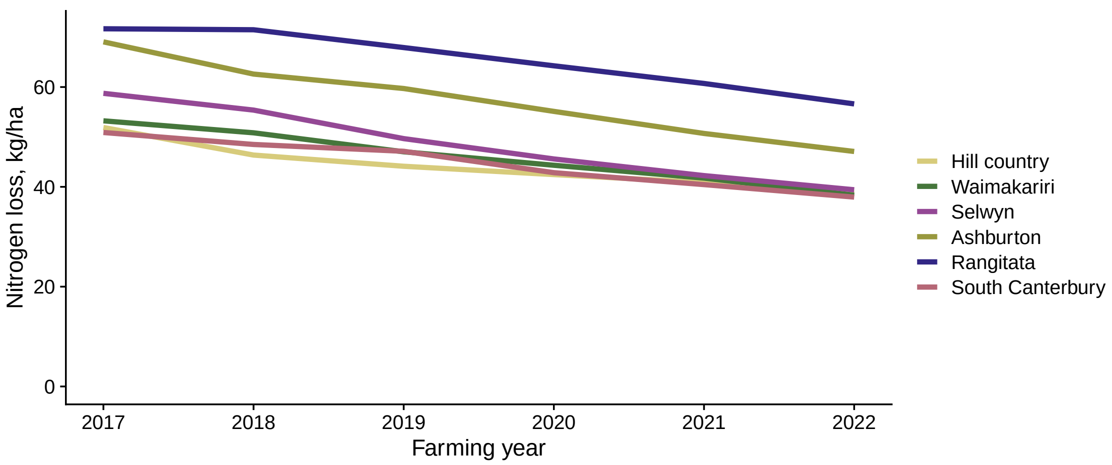

Figure A-5: Mean nitrogen loss per hectare for Canterbury dairy farms, by sub-region (as defined in this study).

Table A-2: Total farm area, productive area, dairy farm characteristics (Dairy; revised stock unit (RSU) and milk production (kg)), nitrogen loss (kg), and mean nitrogen loss per hectare for Canterbury dairy farms, by year and sub-region (as defined in this study).

Year	Sub-region	Farm area, ha		Dairy		Nitrogen loss	
		Total	Productive	RSU	milk, kg	kg	kg/ha
2016–17	Hill country	32 843	31 731	855 972	36 778 627	1 658 082	51.9
	Waimakariri	34 099	31 703	933 901	40 770 561	1 984 284	53.2
	Selwyn	36 316	34 124	1 092 543	47 737 267	2 177 004	58.7
	Ashburton	52 426	49 082	1 671 366	75 787 785	3 530 674	69.1
	Rangitata	48 317	44 918	1 565 598	70 457 643	3 405 292	71.7
	South Canterbury	64 650	58 467	1 725 802	75 036 820	3 205 055	50.9
	Canterbury	269 604	250 927	7 877 324	348 077 571	16 065 146	
2017–18	Hill country	39 492	37 039	976 982	41 207 348	1 682 180	46.4
	Waimakariri	38 234	35 238	1 025 918	44 605 918	2 096 661	50.8
	Selwyn	39 582	36 817	1 176 579	50 572 242	2 218 683	55.4
	Ashburton	61 130	56 072	1 795 854	80 334 298	3 619 461	62.6
	Rangitata	53 070	48 391	1 733 740	78 295 688	3 737 642	71.5
	South Canterbury	73 743	66 570	1 969 382	85 264 561	3 484 740	48.5
	Canterbury	305 964	280 815	8 703 230	381 450 222	16 897 620	
2018–19	Hill country	41 496	38 625	1 032 709	44 235 763	1 721 409	44.1
	Waimakariri	45 074	41 334	1 232 481	54 034 182	2 234 213	47.0
	Selwyn	47 006	41 835	1 366 503	59 489 011	2 375 026	49.7
	Ashburton	62 456	56 702	1 861 706	83 682 305	3 495 969	59.7
	Rangitata	53 543	48 673	1 754 897	80 150 457	3 620 267	67.9
	South Canterbury	73 994	67 064	1 986 455	86 801 114	3 353 420	47.1
	Canterbury	324 211	294 844	9 258 626	409 537 243	16 856 859	
2019–20	Hill country	41 647	38 640	1 061 212	45 378 909	1 724 822	42.5
	Waimakariri	46 850	41 427	1 292 639	57 276 748	2 208 459	44.3
	Selwyn	49 164	43 186	1 417 969	62 176 856	2 259 843	45.6
	Ashburton	63 786	56 005	1 900 182	86 599 140	3 284 632	55.1
	Rangitata	54 249	48 529	1 798 680	82 921 378	3 453 317	64.3
	South Canterbury	79 446	71 045	2 178 334	95 655 998	3 294 890	42.8
	Canterbury	335 925	299 584	9 677 879	431 365 571	16 302 831	
2020–21	Hill country	42 878	39 226	1 093 889	46 619 792	1 716 606	40.9
	Waimakariri	47 142	41 067	1 313 001	58 227 192	2 081 110	41.8
	Selwyn	49 960	43 016	1 436 416	63 309 977	2 112 179	42.2
	Ashburton	65 941	57 088	1 975 733	89 684 403	3 168 428	50.7
	Rangitata	54 477	48 352	1 803 861	83 219 717	3 275 610	60.7
	South Canterbury	81 813	73 169	2 274 800	100 808 168	3 236 043	40.4
	Canterbury	342 994	302 672	9 926 108	443 193 277	15 670 785	
2021–22	Hill country	43 016	38 661	1 081 386	45 667 922	1 643 784	38.7
	Waimakariri	46 512	40 116	1 277 621	56 463 727	1 869 184	38.3
	Selwyn	48 892	41 878	1 394 484	60 808 738	1 931 927	39.4
	Ashburton	62 847	54 720	1 962 020	88 135 504	2 925 337	47.1
	Rangitata	54 596	48 016	1 789 704	82 032 151	3 064 139	56.6
	South Canterbury	82 505	73 148	2 264 940	100 068 916	3 061 413	37.9
	Canterbury	339 331	297 472	9 801 787	434 637 786	14 593 292	

A.4 Nutrient budget analyses published to Environment Canterbury Regional Council and other organisations

Table A-3: Summary (document source publication) of nutrient budget analyses from OverseerFM from Canterbury dairy farms. Records of analyses published to Environment Canterbury Regional Council (ECan) and to other accounts, including mean and median nitrogen loss (kg) per hectare. (Note, these budget analyses were not carried forward.)

	ECAN				Other			
Year	No. analyses	No. farms	Mean N loss/ha	Median N loss/ha	No. analyses	No. farms	Mean N loss/ha	Median N loss/ha
2016–17	24	24	43.9	37.0	343	322	57.8	54.0
2017–18	43	43	43.9	35.0	741	653	55.3	53.0
2018–19	84	84	38.4	36.0	1 327	978	51.7	49.0
2019–20	110	110	37.6	31.0	1 436	1 040	47.1	45.0
2020–21	42	42	39.3	36.5	988	751	43.0	42.0
2021–22	34	34	29.3	26.0	815	674	39.0	37.0

APPENDIX B STATISTICAL MODEL DIAGNOSTICS

B.1 Model selection

Table B-1: Models considered for selection to analyse nitrogen loss data from OverseerFM.

Name	Model formula	Description
A	`n_loss ~ I(log(rsu)) + I(log(stock_rate)) + t2(sub_region,year, bs=c('re', 'cr'))`	Model predicts total nitrogen loss, with covariates accounting for the size of farms in terms of herd size (revised stock unit, RSU) and productive area (stocking rate).
B	`n_loss_per_ha ~ t2(sub_region,year, bs=c('re', 'cr'))`	Model predicts nitrogen loss per hectare. No covariates.
C	`n_loss - I(log(rsu)) - I(log(stock_rate)) ~ t2(sub_region,year, bs=c('re', 'cr'))`	Model predicts nitrogen loss per hectare, adjusted by the size of the farm in terms of RSU and stocking rate. No covariates.

Table B-2: Comparison of the predicted annual rate of change in estimated nitrogen loss by Canterbury dairy farms from the three models initially developed for the current analysis.

Model	Annual rate	95% credible interval	
		2.5%	97.5%
A	-5.7	-1.1	-10.6
B	-5.2	0.1	-10.8
C	-4.1	1.7	-10.4

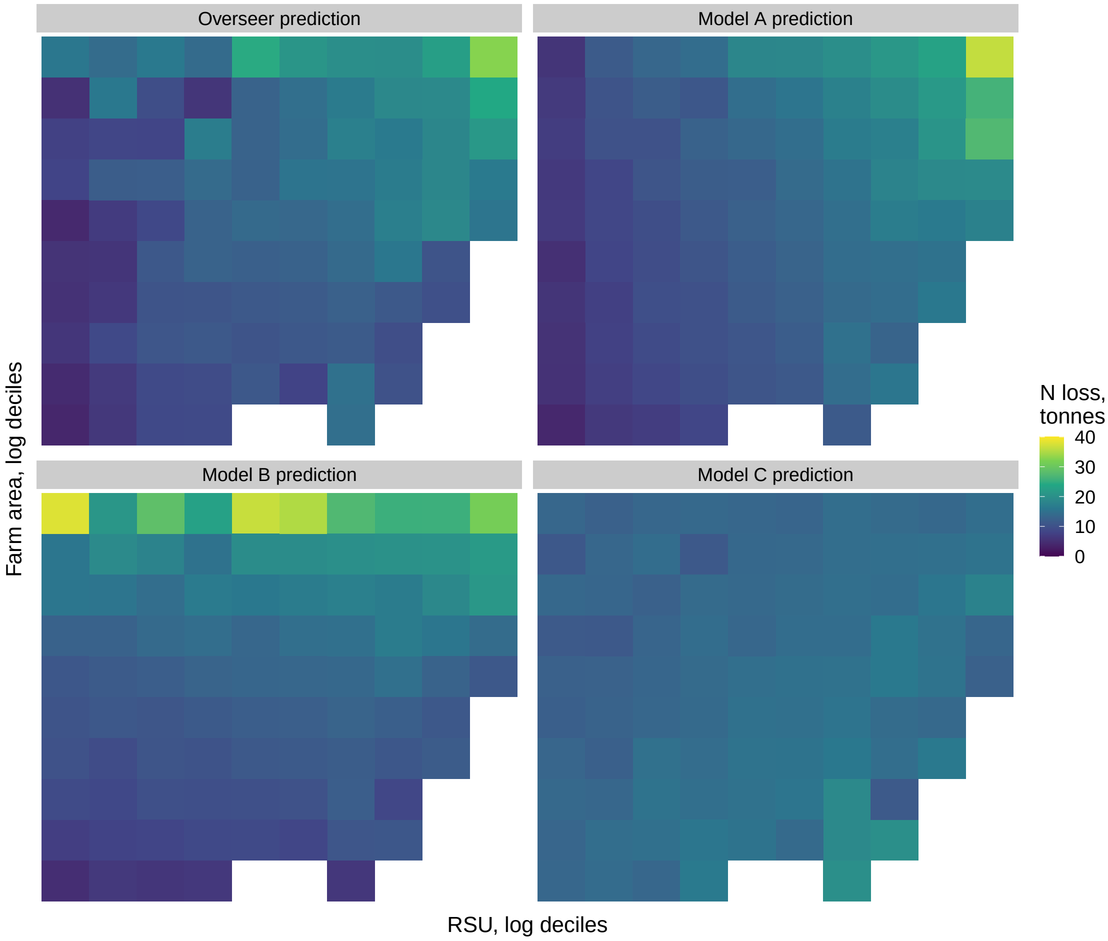

Figure B-1: Comparison of OverseerFM predicted and modelled nitrogen loss response by deciles of log productive farm area (ha) and deciles of log stock numbers (revised stock unit, RSU).

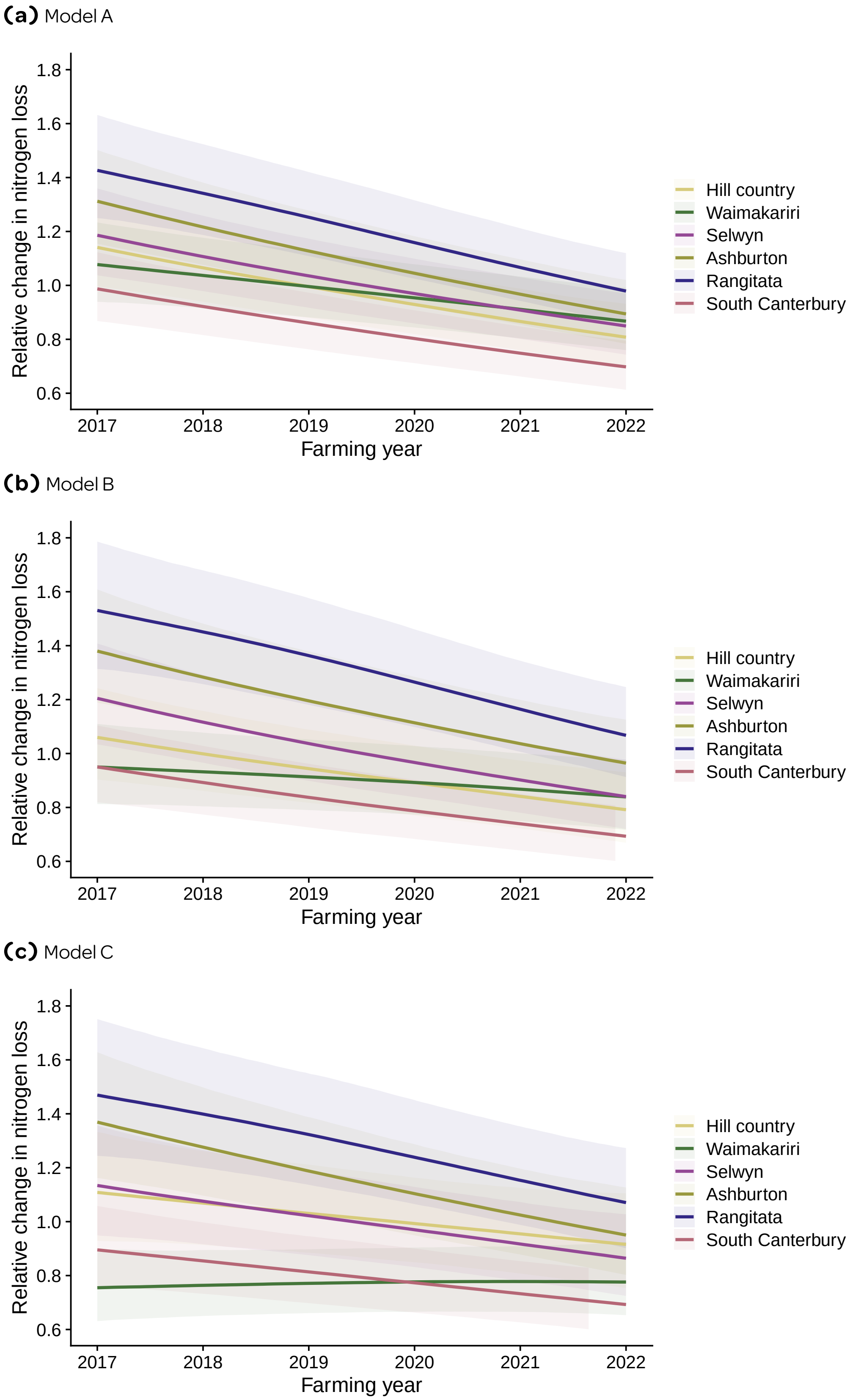

Figure B-2: Modelled effect of year and sub-region, holding the stock number constant. Shading indicates 95% credible interval.

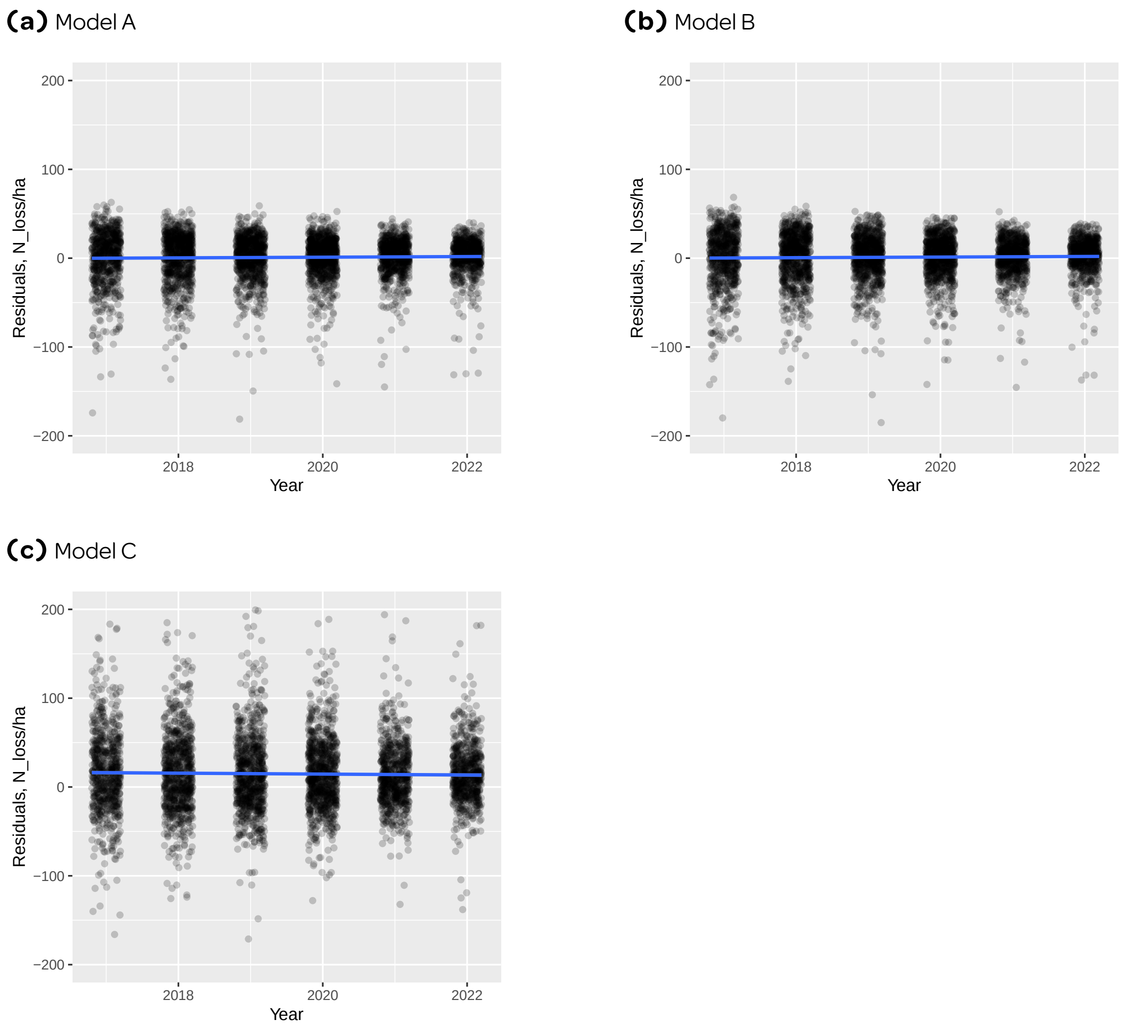

Figure B-3: Residuals by year for each of the models considered for the analysis of estimated nitrogen loss. Years are jittered to support visualisation of the data. Blue line shows mean trend in estimated nitrogen loss.

B.2 Model parameters

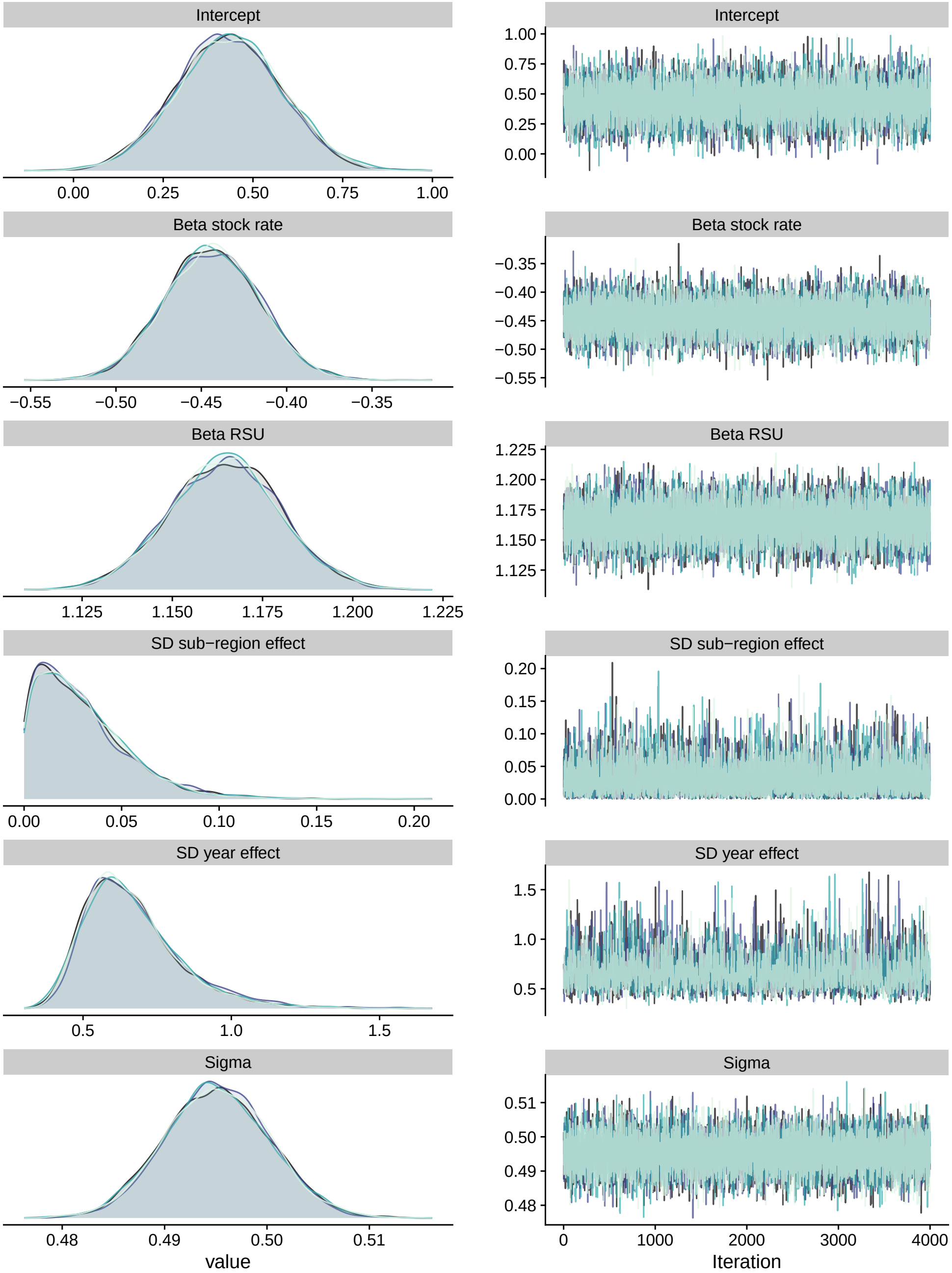

Figure B-4: Diagnostic plot of the posterior densities and traces from the Markov chain Monte Carlo samples for parameters in the statistical model assessing nitrogen loss estimates.

Table B-3: Fit of model parameters. RSU, revised stock unit; SD, standard deviation.

Parameter	Mean	Median	95% quantiles Lower	Upper
Intercept	0.435	0.434	0.149	0.721
Beta stock rate	-0.444	-0.444	-0.498	-0.390
Beta RSU	1.165	1.165	1.135	1.195
SD sub-region effect	0.030	0.025	0.001	0.089
SD year effect	0.667	0.639	0.430	1.074
Sigma	0.495	0.495	0.485	0.505

B.3 Model fit

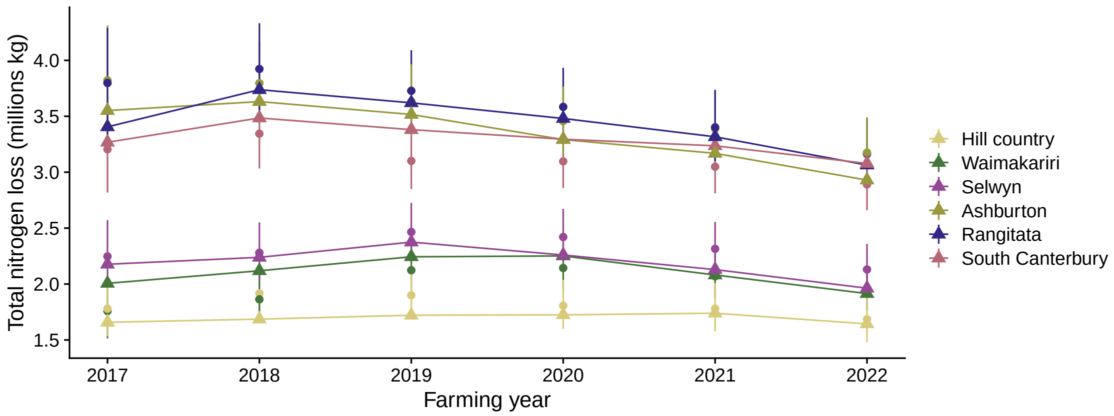

Figure B-5: Annual comparison between total model-predicted nitrogen loss and nitrogen loss reported from the study dataset, by sub-region (as defined in this study). Round points are mean estimates, vertical lines represent the 95% credible interval. Triangles, linked by lines, indicate the total nitrogen loss reported by the OverseerFM model.