Benchmarking and mitigating contaminant losses to water, and GHG emissions to air, for key dairy farm typologies

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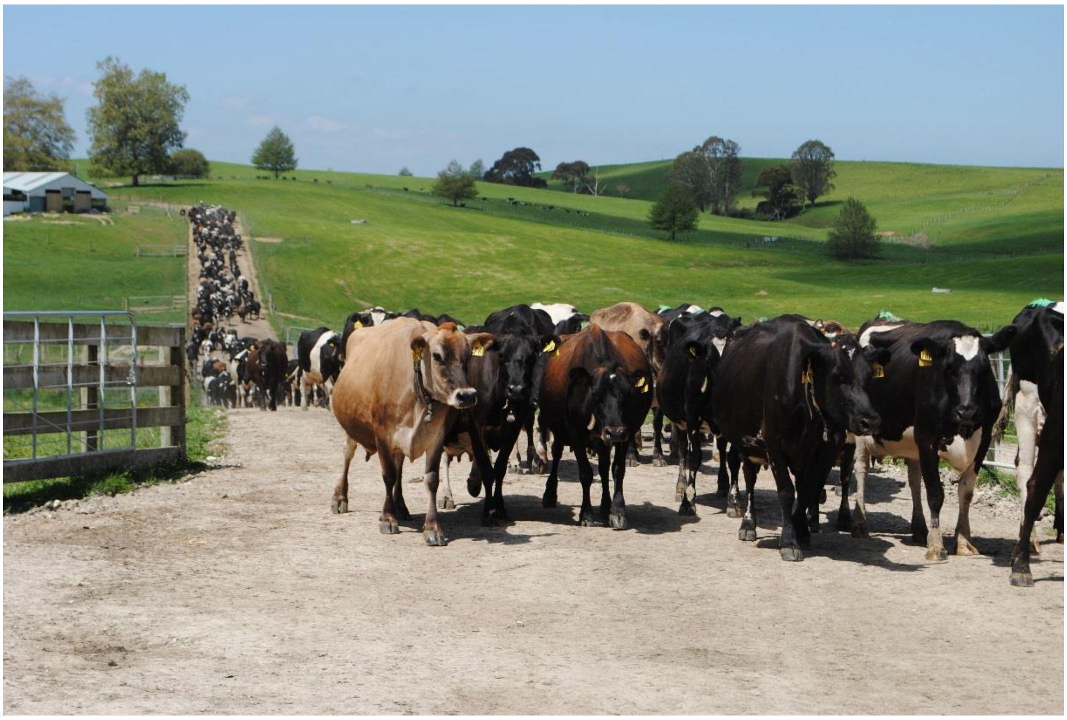

Report for DairyNZ

Client Report Number: RE450/2017/081

[1] DairyNZ

Contents

1. Executive Summary

Quantifying and mitigating contaminant losses to water, and greenhouse gas (GHG) emissions to air, from New Zealand (NZ) dairy farming systems are goals that are urgently sought by Industry and community groups. These goals are challenging undertakings due to the technical complexities created by the wide variability in landscape ***vulnerabilities*** to contaminant loss and the land use ***pressures*** created by land management practices. Landscape vulnerabilities can be defined as the soil, topography and climate factors that are known to influence the inherent risk of contaminant transport to water, whereas land use pressures reflect the diverse set of farm inputs and feed and stock management practices that can have an effect on contaminant sources. Here we describe an approach that seeks to define benchmarks of nitrogen (N) and phosphorus (P) losses to water, and GHG emissions to air, from NZ dairy farms whilst recognising the "inherent" loss risks caused by these landscape vulnerability features. We then extend the approach documented by the European Nitrogen Expert Panel to identify and mitigate farms where land use pressures are greatest. A specific consideration of the effectiveness of reducing soil Olsen P concentrations as a strategy for reducing P loss risk is presented and qualitative/expert assessments of mitigation effectiveness for reducing losses of sediment and faecal microorganisms (FMOs) to water provided. Our analysis was constructed using farm nutrient budgeting information contained within files for actual farms held within the Dairybase database that was provided by DairyNZ.

Our analysis suggests that consideration of landscape vulnerability factors can be a useful approach for benchmarking contaminant losses to water, and greenhouse gas (GHG) emissions to air, from New Zealand (NZ) dairy farming systems. Considerable variability was observed for N and P losses and GHG emissions within most typology categories and/or groups, reflecting the wide variation in land use pressure caused by contrasting farm management practices. This approach would potentially provide an improved set of metrics that could be used as points of reference for farms, thus helping to make assessments of environmental performance more relevant to individual farming circumstances. The attributes used to define these benchmarks do however differ depending on the issue of concern. For N losses to water, we suggest that there could be 7 key typology groupings that consider soil drainage status and wetness as defining attributes: Poorly drained soils, Light soils (Irrigated and "other" (predominantly farms in wet locations)) and Well-drained soils (located in Dry, Moist, Wet or Irrigated environments). For GHG emissions to air, winter temperature, irrigation and topography were identified as key defining attributes that could be amalgamated into 4 key typology groupings: Irrigated farms, Non-irrigated farms in winter warm areas (either Flat or Rolling topography) and Non-irrigated farms in winter cool areas (all farms). Key typology attributes for benchmarking farm P losses were less obvious than discerned for losses of N and GHG, although soil Anion Storage Capacity (ASC), slope, and wetness attributes were observed to have a significant effect on estimated losses. Six typology groupings were suggested for benchmarking P losses: Farms with Low ASC soils (all 4 categories of wetness) and "Other" farms/soils (divided into either Flat or Rolling topography).

An advantage of the typology benchmarking approach described here is that it allows for a more targeted approach to selecting mitigations that are appropriate (and most cost-effective) for a particular typology. Assessments of mitigation measures targeting N losses to water were made for selected farms within the 12 most prevalent individual typology units. These indicated that appreciable reductions (up to 56%) could be achieved if a broad suite of measures was implemented, albeit some are recognised to incur significant cost. Consideration of whole-system N efficiency metrics (i.e. accounting for all of the land area needed to support milk production) for each particular typology grouping was found to be a useful approach for guiding mitigation measures, with greater reductions in N leaching estimated for farms where N surpluses were greatest and NUE values were lowest. Whilst most of the mitigation measures were estimated to deliver reductions in N, P and GHG losses, the use of off-paddock facilities (M7) was noted to lead to increases in the latter.

Detailed interrogation of the farm nutrient budgeting information revealed some valuable lessons that can guide future efforts to improve our understanding of contaminant losses from dairy farms. One of these relates to the information provided in the farm nutrient budget files, which was found to range widely in quality and meant that a large number had to be rejected that did not meet basic criteria. This is a salutary reminder that data input uncertainty can be a more important source of analytical ambiguity than the various approaches and assumptions used to construct the modelling tools that are employed to describe farm performance. Also of note is that most Dairybase farm files did not appear to contain actual soil P test results; assumed values, based on soil test information provided by Balance Agri-Nutrients, were therefore used instead to derive “regionally- and soil-typical” values that were used as inputs for our analysis. A repeat of the benchmarking and mitigation exercise reported here should therefore endeavour to focus on filling some of these gaps in farm input information. Such a repeat exercise would be particularly valuable for capturing on-going changes in farm management and environmental performance.

2. Introduction

The National Policy Statement for Freshwater Management (2011) requires value-based water quality limits to be set for all water catchments by 2025. For many water bodies, a more comprehensive understanding of catchment contaminant loading will be required to inform the limit setting process and to provide a robust evidence base for evaluating management and policy options to meet limits where required. Soil type, slope, drainage characteristics, temperature and rainfall are key factors that are known to influence plant growth and the generation and transport of nutrients and other contaminants in liquid and gaseous forms. Water contaminant losses from farms can vary widely due to these inherent landscape and climate factors, coupled with additional land use pressures created by farm management actions. Commensurately, the effectiveness of mitigation measures to reduce these losses also varies from farm to farm. A better understanding of this variability could provide a more targeted approach to quantifying contaminant losses at a range of scales and guide the implementation of mitigation measures to ensure improved environmental outcomes are achieved for least cost.

A number of management practices that determine farm productivity also influence the potential for nutrient losses to water and air. The most obvious of these can be categorised as management "intensity" factors relating to the levels of inputs of fertiliser and feed to farms, and, commensurately, stock numbers. The rates and timing of these inputs, and the daily managements associated with feeding, moving and milking cows, can vary considerably between farms. When combined with the landscape and climate variability noted above, defining "typical" benchmarks of nutrient losses to water and air is very challenging. Modelling tools can help us to capture and isolate some of these effects. The Overseer® Nutrient Budgets model (Wheeler et al. 2008, 2011; hereafter referred to as OVERSEER) is one such tool that is now widely accepted by the farming and scientific communities and calculates estimates of nutrient flows around, and losses from, New Zealand dairy farms. Using this tool we can explore the relative importance of management, landscape and climate factors in determining dairy farm losses and emissions of nutrients to water or air.

Defining appropriate indicators of farm environmental performance is an important consideration to ensure comparisons between farms are fair and consistent. Indicators thus need to take into account farm productivity and consider all land areas that are required to support the production reported for an individual farm unit. De Klein et al. (2017a) discuss some of the indicators relevant to nitrogen (N) cycling in dairy systems. The N surplus (or N balance), defined as the difference between N inputs and N outputs, is a commonly used metric for assessing the risk of environmental losses (e.g. Treacy et al. 2008; Oenema et al. 2012). Optimum targets for N performance indicators would be those aiming for high utilisation of N input while minimising N loss risk and not compromising agricultural productivity. A European Nitrogen Expert Panel recently suggested using a Nitrogen Use Efficiency (NUE) indicator in a two-dimensional framework of N output over N input that combines the different indicators (EU Nitrogen Expert Panel 2015; Figure 2.1). This framework considers the minimum amount of N input required for production, the maximum N surplus that is environmentally acceptable, the minimum NUE level to avoid wasting N and the maximum NUE to avoid soil mining (e.g. Lassaletta et al. 2014). Once goals are set for these parameters, the indicator framework can be applied to assess whether desired outcomes are achieved. Similar principles may also be applied to considerations of phosphorus (P) balances and potential losses from farm systems.

In this report we seek to extend the approach documented by the European Nitrogen Expert Panel by applying the methodology to key dairy agro-ecosystem typologies that encompass the broad range of landscape and climate factors and management systems typical of dairy farming in New Zealand. This step will help to define benchmarks of N and P losses to water and greenhouse gas emissions (GHG) emissions to air that consider the inherent loss risk caused by landscape and climate features. The effectiveness of a number of Good Management Practices (GMPs) recommended for reducing N and P losses to water is then assessed for selected farms within each typology. Estimates of mitigation effectiveness for reducing losses of sediment and faecal microorganisms (FMOs) to water for these GMP measures are also provided. In the case of sediment, estimates were made using an inventory approach that included surface erosion estimates derived using the Revised Universal Soil Loss Equation (Renard et al. 1997); for FMOs, qualitative estimates were derived based on expert assessment.

The purpose of this report is to provide quantitative information on typology-specific nutrient losses from farms to support DairyNZ in developing an accounting framework for evaluating the potential impacts of dairy farming on water quality at catchment, regional and national scales. This work will also improve understanding of mitigation efficacy across different landscape and farm management typologies, thus better informing potential management options that can assist farms to meet environmental limits.

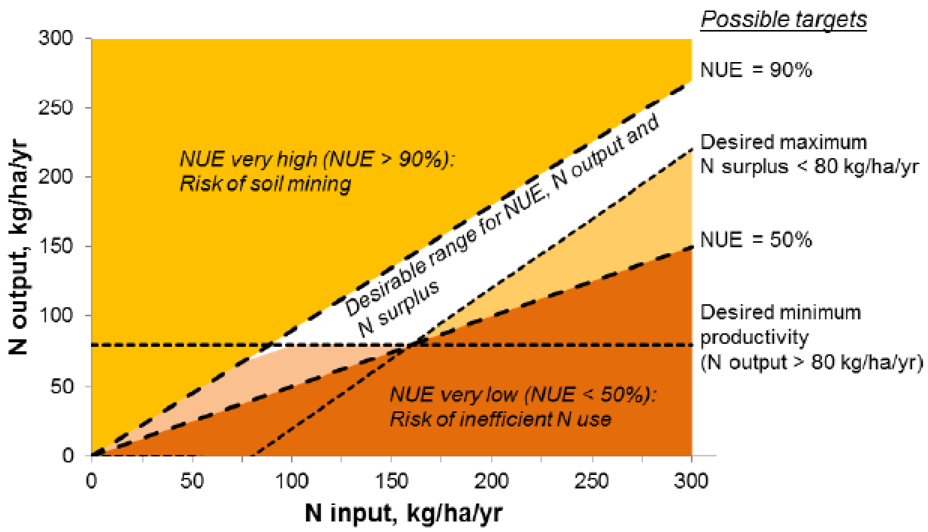

Figure 2.1. Conceptual diagram of the nitrogen use efficiency (NUE) indicator framework developed by the EU Nitrogen Expert Panel (2015). The numbers shown are illustrative of an example system and will vary according to context (soil, climate and crop or grazing system). The slope of the diagonal wedge represents a range of desired NUE values within 50–90%; lower values are likely to exacerbate N loss and higher values risk mining of soil N stocks. The horizontal line is a desired minimum level of productivity for the example system. The additional diagonal line represents a limit related to maximum N surplus to avoid substantial pollution losses. The combined criteria serve to identify the most desirable range of outcomes and is represented by the un-shaded part of the figure (from de Klein et al. 2017a).

3. Methods

Our analysis was undertaken in three parts. The first focussed on defining farm attributes in key dairy agro-ecosystem typologies[1] that encompass the broad range of landscape - environmental features and management systems typical of NZ dairy farming. These were defined using GIS layers of a number of landscape features that influence the inherent loss risk of nutrients and GHG from different farm types within each agro-ecosystem (i.e. temperature, rainfall, topography, soil type, soil drainage class and soil anion storage capacity (ASC) values). The second part of the project aimed to define benchmarks of N, GHG and P losses that consider the inherent loss risk due to the landscape and climate

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[1] Typology is a classification according to general type, and as used here refers to climate and landscape attributes

features categorised in part 1 above. The third part of the project identified and assessed the effectiveness of GMP measures recommended for their potential to reduce losses of N, P, sediment and FMOs to water. As we used OVERSEER for this analysis, we were also able to provide benchmarks of GHG emissions and provide an initial assessment of the impact of the GMP measures on GHG emissions. Here we define total GHG emissions as the methane (CH_4) plus nitrous oxide (N_2O) emitted from the farm system.

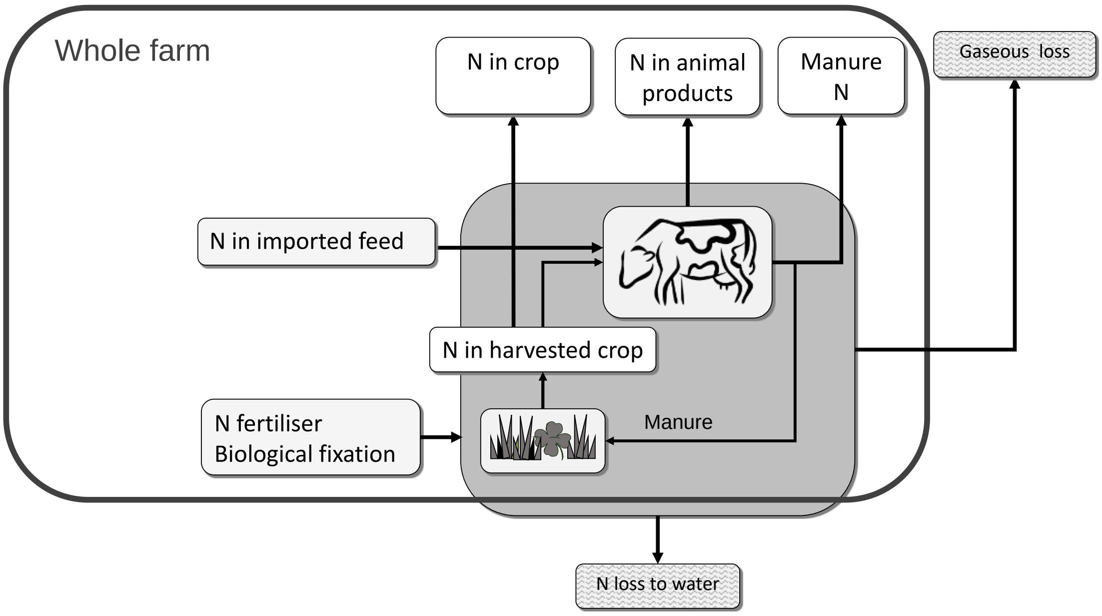

Figure 3.1. Representation of the N inputs and outputs that need to be considered in calculations of whole-farm NUE and N surplus values. Milking platform boundary represented by grey shading (from de Klein et al. 2017a).

3.1 Defining farm attributes in key dairy agro-ecosystem typologies

A hierarchical analysis of primary landscape and climate attributes that influence contaminant losses to water identified five factors that could potentially be used to classify dairy farms into discrete typologies. This approach extended (and in some cases, simplified) some of the concepts originally presented and discussed in a working paper by Hewitt et al. (2007) and Lilburne and Webb (2015). Each factor and its relevance to contaminant transport is briefly described below.

1. **Temperature:** Soil temperature influences pasture production and in turn farm system attributes. For example, cooler areas will experience longer periods of low pasture growth over the winter months and relatively low evapotranspiration. These areas are more likely to feature farms with grazed forage crops during winter. Two temperature classes were defined based on mean June soil temperatures (30 cm depth; data layer derived from LENZ 2018):
    a. Warm: mean June soil temperature greater than 4ºC
    b. Cool: mean June soil temperature less than 4ºC

2. **Wetness:** Surplus rainfall is known to directly influence the transport of contaminants through (Cichota et al. 2012) and over (McDowell et al. 2005) soil. Dairy farms located in areas where rainfall is low are likely to be irrigated. Four classes of wetness were therefore distinguished based on OVERSEER file information:
    a. Irrigated farms: irrigated land area exceeds 50% of farm area
    b. Wet farms: rainfall exceeds 1700 mm per annum
    c. Remaining farms were then classified into Dry or Moist categories based on the lower or upper 50th percentile categories, respectively, for calculations of surplus rainfall [Rainfall – actual evapotranspiration], as derived from the OVERSEER farm file

3. **Soil Drainage:** This classification attempts to capture the effects of two fundamental processes that influence the vulnerability of soil to nitrate leaching. The first is that of N displacement from soils that have contrasting abilities to store water and nutrients; Plant Available Water (PAW) holding capacity was chosen as the soil attribute that best represented this aspect of leaching vulnerability. The second process considered was soil denitrification whereby nitrate is reduced and removed from the soil via gaseous forms. Soil drainage status, as defined in the Land Resource Information System (LRIS) soil map layers (Newsome et al. 2008), was chosen as the attribute that best represented this aspect of N leaching vulnerability. Three classes of soil drainage were then determined:
    a. Light soils: soils with PAW_{60cm} contents of less than 85 mm
    b. Well-drained soils: well or moderately well drained soil drainage classes as defined in the LRIS mapping system
    c. Poorly-drained soils: imperfect, poor or very poor soil drainage classes as defined in the LRIS mapping system

4. **Slope:** Topography influences contaminant runoff and land use suitability. Two slope classes were distinguished, primarily to reflect the vulnerability of land to P runoff (McDowell et al. 2005):
    a. Flat/Undulating: slope 0 – 7°
    b. Rolling: slope >7°

5. **Anion Storage Capacity:** This measure is an index of the ability of a soil to retain anionic forms of P in soil solution. Soils with low (e.g. < 10%) ASC are particularly prone to large losses of P. Soils were classified into the following three categories:
    a. Low ASC soils: ASC values < 10%
    b. Medium ASC soils: ASC values between 10 and 60%
    High ASC soils: ASC values > 60%

Average values for drainage and ASC attributes for each farm were estimated based on the soil descriptions in OVERSEER for each farm (i.e. soil sibling from S-Map, soil order or soil group) which have default PAW and ASC values assigned (Wheeler 2016). If more than one soil type was present on a farm then an area-weighted average value was calculated.

There are potentially 144 typology possibilities (2 x 4 x 3 x 2 x 3) based on the above classification system. Because ASC is a factor with no relevance to estimates of N loss, N typologies are limited to 48 possibilities (2 x 4 x 3 x 2).

3.2 Constructing the typology spatial framework

Based on the defining farm and landscape attributes described above, the following spatial layers were utilised to initially develop the typology framework:

- For information on the river networks in New Zealand, we used the 2010 release of the River Environment Classification system (Snelder et al. 2010). This is a powerful resource management tool that organises and maps information about the physical characteristics of New Zealand's rivers, including catchment climate, topography, geology and land cover. Information is mapped by individual river segment for New Zealand's entire river network. From this resource management tool, we extracted information on the climatic conditions of the riverine sections running through dairy farms in New Zealand, specifically classifying large-scale catchment reaches into Cool-Extremely Wet, Cool-Wet, Cool-Dry, Warm-Extremely Wet, Warm-Wet, Warm Dry from combinations of Rainfall-Less Evapotranspiration and temperature regime. As we derived wetness conditions from other data sources, we further reduced these categories to Winter-Warm, Winter-Cold. These categories are important for nutrient cycling, bacterial growth and mortality which are of importance to this project, as well as on a more general level the habitats it creates for aquatic biota.
- Irrigated farms were assigned to the typology framework based on an adaptation of the LENZ framework ("Data reproduced with the permission of Landcare Research New Zealand Limited") combined with data for 10 year rainfall averages from NIWA's virtual climate stations as Severe Water Deficit (Irrigated: Annual Rain-deficit greater than 100 mm). Initial categories assigned were: Occasional Water Deficit (Supplemental Irrigation: Annual Rain-deficit 20-100 mm), Rain-Fed (No Irrigation: Annual Rain-deficit 0-20 mm), and Wet (Wet: 10 year rainfall average greater than 1700 mm per annum).
- Soil drainage class and ASC (historically referred to as "P-Retention") attributes were derived from The New Zealand Fundamental Soil Layer (FSL, Data reproduced with the permission of Landcare Research New Zealand Limited), which originates from a relational join of features from two databases: the New Zealand Land Resource Inventory (NZLRI), and the National Soils Database (NSD). Some of these attributes originate from exact matches with NSD records, while others derive from matches to similar soils or professional estimates. This layer contains attributes relating to soil drainage. Soil drainage is described as a class. Drainage classes are assessed using criteria of soil depth and duration of water tables inferred from soil colours and mottles. Drainage classes used here are the same as those used in the NZ Soil Classification (Hewitt 1993), and outlined by Milne et al. (1995).
- Drainage characteristics of "Well" or "Poorly" drained soils were defined from the FSL, where classes 4-5 were deemed to be well drained, and classes 1-3 poorly drained. The remaining drainage classes were omitted from our framework.
- ASC values, also derived from the FSL, were categorized as Low (0-10%), Moderate (10-60%), or High (60-100%).
- New Zealand National Digital Elevation Model: a 25 metre resolution, floating point precision, elevation grid generated from the LINZ 1:50,000 scale Topographic data layers (20m contours, spot heights, lake shorelines and coastline) using

Landcare Research's in-house interpolation software ("Data reproduced with the permission of Landcare Research New Zealand Limited”). This digital elevation model was used to derive and classify slope into three distinct categories of 0-7 degrees, 7-15 degrees, and above 15 degrees. This allows for both detailed spatial calculations of the amount of land on a farm that falls into these distinct categories, as well as to code individual dairy units based on the dominant slope category.

- Polygon coverages of dairy units across NZ were then used on all of the above layers to calculate the areal extent of the spatial co-occurrence, rendering a dairy polygon coverage with the detailed information from these layers. Additionally, areas of bush and forest cover derived from the New Zealand Landcover Database Version 4 (Creative Commons Attribution 3.0 New Zealand) were used to extract out the extent of areas within the polygons that had likely been decommissioned for use as pasture. After this last step, each dairy polygon was given a dominant class for each individual data type (binary coding).

Preliminary analysis showed that a revised approach was needed to overcome gaps in some of the above information layers; this modified approach is further explained in section 4.1.

3.3 OVERSEER farm file information

OVERSEER files for actual farms held within Dairybase were provided by DairyNZ and used to build the datasets that are documented and reported here. The locations of these 431 farm files are shown in Figure 3.2. Assessments were undertaken at two scales (explained further in section 3.4):

i. For the areas represented in the Dairybase OVERSEER files: In many instances these were partial representations of the total farming systems due to the absence of land areas needed to support milk production e.g. winter crop land and areas used to support young stock or provide supplements for feeding on the milking platform. Results are however reported here to allow for potential use in other modelling initiatives where spatially-discrete representations of N and P discharges and GHG emissions may be required.

ii. At a whole farm scale (i.e. all hectares counted): This allows consistent comparisons to be made between farms. This scale of analysis helps to avoid some of the confusion created by earlier reports that document losses and mitigation effectiveness at partial-farm, paddock or block scales. Representations of areas of land that were not represented in the Dairybase OVERSEER files were derived (or “back-filled”) from OVERSEER files that were constructed for the different types of support land areas. These default files were in turn constructed based on representative soil, climate and management attributes deemed appropriate to the farm typology for which the Dairybase OVERSEER file had been assigned.

The quality of all OVERSEER farm files supplied by DairyNZ was assessed prior to analysis. Criteria considered when assessing quality and deciding whether or not a farm should be included in the analysis are listed in Table 3.1, with more detailed criteria listed in Appendix 9.1. Farm files were not corrected unless there was an obvious unambiguous fix or additional information describing farm conditions or operation was readily available.

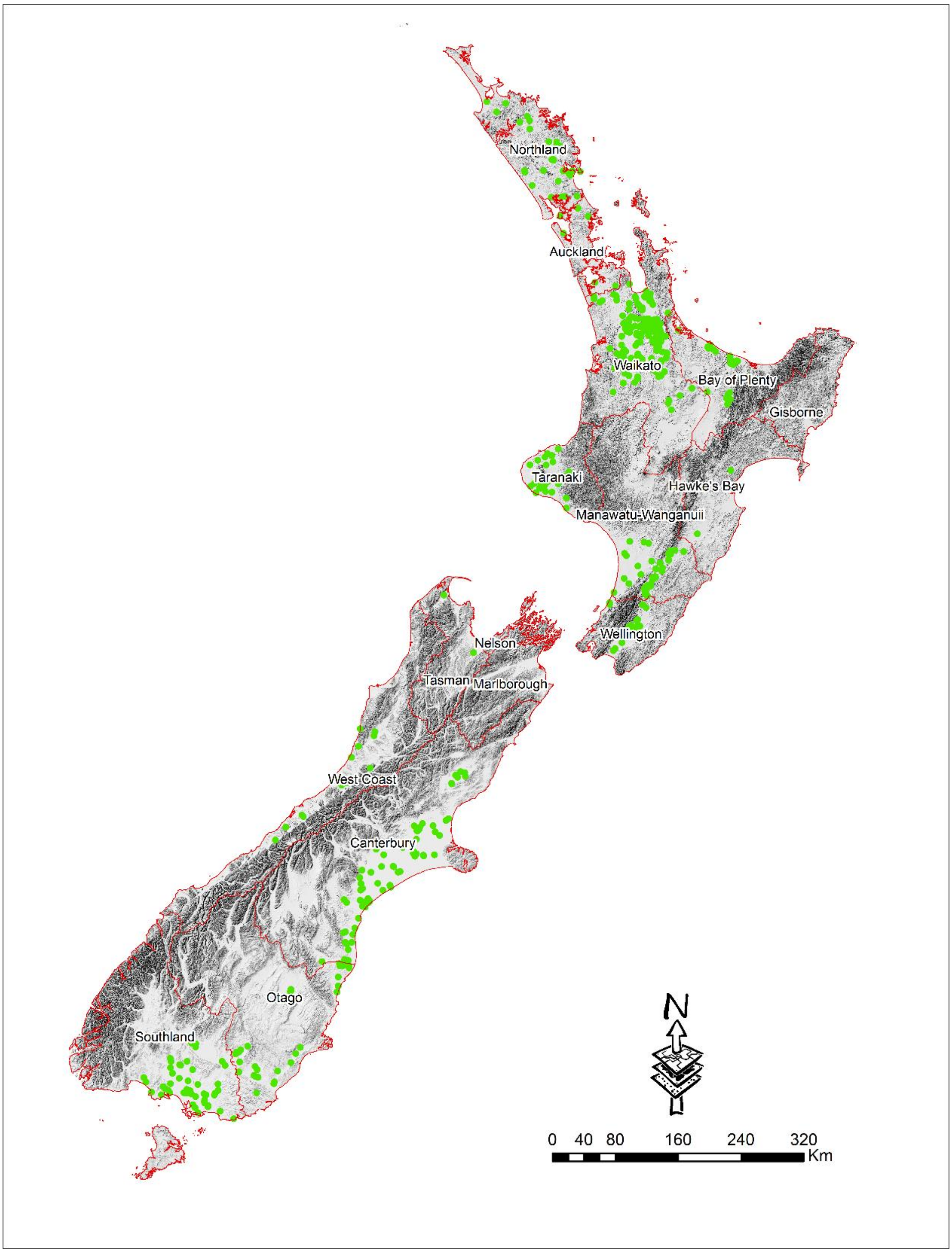

Figure 3.2. Locations (marked in green) of the 431 OVERSEER dairy farm files received from Dairybase records.

Several farms had one or more blocks for which soil type was derived using either soil group or soil series selection and in some cases the block name included the name of a soil sibling or series. In the absence of more precise information it was assumed that this was credible and provided an improved description of the block's predominant soil.

Some inaccuracies or lack of precise information observed in OVERSEER farm files were widespread (Table 3.2). Excluding these files would have severely limited the number of files available for analysis and these were therefore overlooked when assessing file quality for inclusion.

Table 3.1. Criteria and preferences/rationale considered when assessing the suitability of OVERSEER farm files

Criteria	Preference / Rationale
Nutrient budgets must be available	Difficult to verify fix when farm data is unavailable
OVERSEER estimates of milk and pasture production are realistic (i.e. production falls within a realistic range given region and farm system type)	General test for sensibility of farm system
Stock numbers, movements and weights are sensible	Monthly numbers preferred to specifying peak number of cows in herd
There is a coherent effluent management system (e.g. effluent is not applied to mature crop)	Required to implement mitigations – farms were excluded if all effluent was exported
Climate is specified using the OVERSEER Climate Station Tool	OVERSEER best practice[1]
Soils are described using soil siblings or series	OVERSEER best practice[1] – use of soil order and soil group to describe soils is considered inadequate for this
Minimal export of supplements	May potentially skew data
Advanced settings only used when reason for doing so is apparent	Farms in transition not preferred
Irrigation management method is specified	OVERSEER best practice[1]

[1] OVERSEER Best Practice Data Input Standards Version 6.2.3 (November 2016).

Table 3.2. Inaccuracies in OVERSEER farm files not considered when assessing file quality.

Inaccuracy	Likely impact on contaminant loss estimates
Replacements not recorded on farm until weaned from milk	Negligible – intake of young calves is small compared to the milking herd
Fertiliser applications spread evenly over all pastoral blocks within the farm (an assumption made when application location is unavailable).	Likely to have a greater effect on farm level nutrient losses where soils differ markedly from block to block
Soils with poor or imperfect drainage yet no artificial drainage systems.	Effect uncertain

OVERSEER files that were deemed acceptable (309 farm files in total) for benchmarking purposes and further analysis were then assigned to a typology based on the inherent loss risk factors described in section 3.1.

3.4 Benchmarking approach

Two approaches were taken for benchmarking farm loss estimates. For N and GHGs, loss estimates were derived using an approach that attempted to consider all land area required to support milk production on each farm. This approach was deemed important because it readily became apparent that the available OVERSEER farm files represented different components of the dairy system: some files were constructed to just represent the pastoral land used to feed milking cows (i.e. the milking platform), whilst others were constructed to capture all land units required to feed and support the milking herd (i.e. milking platform pastures, wintering blocks and areas used for supplement provision or supporting young stock). This consideration of all hectares or whole-system losses is important for providing more representative comparisons between farms, particularly where some blocks, such as wintering areas, are recognised as making disproportionately large contributions (relative to area) to farm losses of N and GHGs. Estimates of N inputs and N and GHG outputs from “missing” areas of the OVERSEER farm files were therefore derived from default OVERSEER files that were set up to describe regionally-representative production systems from these “missing” areas. Whole-system emissions of N and GHGs were then computed based on actual OVERSEER farm file outputs and assumed supplementary outputs from the support land omitted from these files.

In the case of P losses, analyses were instead undertaken on the “effective” farm areas of 248 OVERSEER farm files. Preliminary quality checks of farm files had identified that a high proportion (78%) had not used measured Olsen P data, but instead had used default OVERSEER Olsen P values. These default values are based on average Olsen P for different soil types sourced from the National Soils Database. Whilst these default soil test values can be used if the interest is solely focussed on nitrogen losses or greenhouse gas emissions (OVERSEER Best Practice Data Input Standards Version 6.2.3, November

2016), they were not suitable for the benchmarking purposes of this study and the boundary of the analysis was therefore confined to the effective farm areas of the OVERSEER files.

To address this problem, regional soil Olsen P test values supplied by Ballance Agri-Nutrients were used to replace OVERSEER default values, giving indicative estimates of (i) P loss risk by region, and (ii) potential reductions in P loss that could be achieved by region. The updated Olsen P dataset represents soils sampled in 2015 from dairy farms for four of the main soil groups across New Zealand. This includes the Sedimentary soil group (11,640 samples from 1416 farms), the Volcanic soil group (2867 samples from 673 farms), the Pumice soil group (1346 samples from 228 farms) and the Peat soil group (763 samples from 161 farms) soils. Unfortunately, no data was provided for the Podzol group. In this instance the average Olsen P value for Podzol soils reported in a survey of 40 dairy sites in Southland was used for that region (Simmonds et al. 2015). A search of the literature also highlighted a dearth of available Olsen P data for Podzols in the two other regions (Northland and Waikato) where they are present (albeit only a very small numbers of farms, 1 and 3 farms respectively). For those regions we used the same average value we used for Sedimentary soils, recognising that Podzols have previously been reported by Edmeades et al. (2006) as having the same agronomic range for Olsen P as Sedimentary soils. A summary of the replacement Olsen P values used for each soil and region are given in Table 3.3.

The GHG emission estimates in OVERSEER are consistent with the New Zealand national GHG inventory methodology (Wheeler et al. 2008). Methane emission estimates are based on animal energy requirements and associated dry matter intakes (DMI) and a methane yield of 21.6 g CH_4 per kg DMI. Nitrous oxide emissions estimates are based on the amount and form of N in the farm system, multiplied by the relevant N_2O emission factor (expressed as % of N_2O-N emitted per unit of N) for each source of N. OVERSEER has three different options for setting the N_2O emission factors. However, as there currently are some uncertainties around two of the options (de Klein et al. 2017b), we used the “annual average” emission factor option, using the same values as those of the New Zealand national GHG inventory methodology. These emission factors do not account for any agro-ecosystem differences (e.g. due to climate or soil). Differences in N_2O emissions are therefore solely driven by difference in the amount and form of N in the farm system.

Table 3.3. A summary of the regional average Olsen P values assigned for each soil group (source: Ballance Agri-Nutrients Ltd).

Region	Sedim.[1]	Volcanic	Pumice	Podzol	Peat	Other[2]
Northland	35	42	-	35	41	35
Auckland	36	43	47	-	65	36
Waikato/Coromandel	45	41	50	45	44	45
Bay of Plenty	47	44	49	-	49	47
Taranaki	40	44	-	-	41	40
Manawatu/Wanganui	34	42	-	-	41	34
East Coast North Is	28	34	-	-	-	28
Nelson	28	-	-	-	-	28
West Coast South Is	28	-	-	-	-	28
Canterbury	29	37	-	-	-	29
Otago	28	-	-	-	-	28
Southland	27	-	-	24	35	27
Northland	35	42	-	35	41	35

[1]mostly Brown soils; [2]mostly Recent, Pallic and Semi-arid soils.

3.5 Mitigation assessments

The third key objective of the study was to assess the effectiveness of a range of mitigation measures on contaminant losses from representative OVERSEER farm files within each farm typology. If load reductions were clearly different between typologies, there is probably merit in targeting extension messages to those farms where the largest reductions are likely to be achieved. An assessment of the effectiveness of specifically reducing soil Olsen P concentrations was also undertaken; the details of the approach used and key findings are documented in Appendix 9.2. This section summarises how farms were defined and mitigations were implemented.

3.5.1 Defining farms to mitigate

Two subsets of farms within each of the 12 most abundant typologies (i.e. those that were identified to cover most of New Zealand's dairy land) were selected for mitigation modelling. The subsets of farms chosen within each typology were those that were categorised as either relatively "highly efficient" (HE) or "less efficient" (LE) based on where their efficiency metrics plotted on the framework outlined in Figure 2.1. In general, the specific criteria for this categorisation were:

- HE farms: N surplus < 200 kg N $ha^{-1}yr^{-1}$; product N output > 50 kg N $ha^{-1}yr^{-1}$; NUE > median for that typology; OVERSEER file area represents >70% of estimated whole system area.
- LE farms: N surplus > 200 kg N $ha^{-1}yr^{-1}$; NUE < median for that typology; OVERSEER file area represents >70% of estimated whole system area.

Due to time constraints, the number of farms selected within each typology subset was restricted to a maximum of 6; for some typologies (4 in total) where farm files were limited in number, fewer farms were available that met the qualifying criteria explained above and thus fewer farms were selected for mitigation modelling within that particular typology. Due to the limited availability of farm files for some typologies, some farms where the OVERSEER file represented less than 70% of the whole system total were included in the mitigation modelling analysis. This resulted in 23 farms in the mitigation dataset having an OVERSEER file that was calculated to represent less than 70% of the whole dairy system area; nine of these represented less than 65%. In total, 137 farms were selected for mitigation modelling.

3.5.2 Description of mitigations implemented

Mitigations were grouped into seven categories (“bundles”, similar to the approach documented in Vibart et al. 2015) that targeted specific aspects of the farming system (Table 3.3). These bundles were progressively applied to selected HE and LE farms in an order that was deemed to be most feasible, based upon cost and practicality. The first bundle of measures (M1) was applied to the base farm (i.e. the original Dairybase farm file, which may or may not have been mitigated already), then the second bundle (M2) was applied to that, and so on. Only those mitigations relevant and appropriate to the systems of each typology were selected and modelled using OVERSEER e.g. improved irrigation (M4) was only applied to the two typologies where irrigation was practised, and the low solubility P fertiliser scenario (M1) was only applied to typologies with poorly drained soils or sloping contour. Mitigation bundles were designed such that if the first bundle (M1) was implemented, farms could be considered to be managed under current good practice. Similarly, if mitigation bundles M2- M4 were implemented, farms could be deemed to be operating under improved practice. Mitigation bundles M5 – M7 could be considered as advanced practice. The assumptions used and changes made within OVERSEER to apply these mitigations are detailed in Appendix 9.3.

Table 3.3. Management strategies and mitigation practices applied to selected HE and LE farms.

Management strategy	Implemented mitigation practise
(M1) Tidy base farm	Stock excluded from streams Olsen P @ agronomic optimum Low solubility P fertiliser sources used where needed i.e. typologies with poorly drained soils or sloping contour P fertilisation is outside high risk months Feed storage facilities are designed to minimise wastage, leachate loss and soil damage, i.e. sealed or compacted surface Avoid or reduced fertiliser N use over winter Reduced monthly N fertiliser application rates to pasture to 40 kg N/ha, non-irrigated; 50 kg N/ha irrigated, or less Reduced N fertiliser applied to crops if greater than recommended guidelines for industry Strategic grazing of winter forage crops Managed runoff from tracks and races Managed runoff around gates and troughs Managed stock crossings
(M2) Improved effluent management	Changed from a two-pond system to land application and/or implemented deferred effluent irrigation Implemented active management - assume appropriate management to eliminate incidental losses of effluent P, etc. Effluent block(s) enlarged so that K inputs <75 kg K ha^{-1} yr^{-1} and combined fertiliser+effluent+supplement-N <200 kg N ha^{-1} yr^{-1} Low rate effluent application methods used on farms in typologies with poorly drained soils and sloping contour Effluent storage sized to meet requirements as per DESC[1] for farms in typologies with poorly drained soils and sloping contour
(M3) Reduced N imports – stage 1	N imported in fertiliser and supplements reduced to the median import for that typology Low N feeds included in the autumn/winter diet
(M4) Improved irrigation	Water irrigation management improved
(M4VV) Improved irrigation (aspirational)	Water irrigation management improved and variable application rate and return period strategy implemented
(M5) Wetlands	Install artificial constructed wetland
(M6) Reduced N imports – stage 2	N imported in fertiliser and supplements reduced further to the 25th percentile for that typology
(M7) Off-paddock management	Wintering strategies implemented (i.e. use of herd shelters)

	Restricted grazing of pastures from March to July to reduce autumn and winter urine N deposition

[1]DESC = Dairy effluent storage calculator https://www.dairynz.co.nz/environment/effluent/effluent-storage/dairy-effluent-storage-calculator-desc/

3.5.3 Assessments of reductions in sediment loss risk

Assessments of reductions in sediment losses in response to the implementation of mitigation measures were sought as part of the analysis undertaken in this study. The tools available to undertake this type of analysis for grazed farming systems are unfortunately rather limited and few have been designed to describe the consequences of animal treading on sediment discharges to water. One potential approach is to calculate an inventory of likely sediment sources on farm and compute the expected reductions in loss in response to the implementation of mitigation measures that are relevant to controlling sediment loss. For the dairy farms evaluated in this study some key sources are likely to be stream bank (and bed) erosion, surface erosion, discharges from mole-pipe drains and surface runoff from farm lanes. Relevant mitigation measures for controlling sediment losses from some of these sources are stock exclusion from streams, strategic grazing of crops, preventing laneway runoff and off-paddock managements. Appendix 9.8 describes how these sediment sources were calculated and the assumptions made for assessing sediment loss reductions in response to some of these measures. Given our limited ability to model sediment losses at a farm scale, it should be emphasised that results are provided as qualitative assessments of the likely responses to mitigation and should not be considered as quantitative estimates of sediment yields from farms and catchments where other erosion processes may be active (such as gully and hill slope erosion) and sediment deposition and re-mobilisation can be important processes influencing overall sediment yields. These qualitative assessments are presented and briefly discussed in section 5 (Discussion) of this report.

3.6 Statistical analysis

ANOVA was used as a first step to assess whether at least one of the typologies was different to others in terms of the key environmental indicators considered here. If this was not the case, there would be no reason to continue with the proposed typology approach. Because many of the typology categories had relatively few Dairybase OVERSEER farm files available for analysis, statistical analysis was therefore confined to the 12 most common farm typologies. These 12 typologies represented 93% of the total (useable) files available. As hypothesised, there was strong evidence that most of the indicators were significantly ($P<0.001$) different between typologies. Deeper investigation was then undertaken based on a mixed model via REML (restricted maximum likelihood) analysis. This approach was chosen because the allocation of farms to typology characteristics based on slope/wetness/drainage/climate attributes was not balanced. The order in which typology attributes were considered in this analysis was important: the effects of some attributes were found to be of minor importance once some of the key attributes had been factored into the mixed model. This approach (i.e. order) therefore varied between some of the indicators depending on which typology attribute was found to be of greatest importance.

4. Results

4.1 Key dairy farm typologies

Preliminary analysis using the GIS layers described in section 3.2 quickly revealed that major gaps in spatial coverage (soil maps in particular) prevented many farms from being explicitly assigned to typologies as first planned. A revised approach was therefore undertaken whereby slope, drainage, wetness and ASC attributes were assigned based upon block-level information contained within each OVERSEER farm file; area-weighted values for each attribute class were calculated and used to do this based on the dominant farm typology attribute. For example, a farm with rolling land/blocks that represented more than 50% of the OVERSEER farm file area was assigned to a "rolling" topography. Of the 431 OVERSEER files received from Dairybase records, 309 were deemed suitable for the benchmarking objective of this study. The regional breakdown of the usable Dairybase farm file set was as follows:

- North Island: 125 (40%) farms were located in Waikato; 18 (6%) farms were located in Bay of Plenty; 18 (6%) farms were located in Taranaki; 18 (6%) farms were located on the East Coast of the North Island; 16 (5%) farms were located in Manawatu; 15 (5%) farms were located in Northland and 1 farm was located in the Auckland region
- South Island: 47 (15%) farms were located in Canterbury; 29 (9%) farms were located in Southland; 16 (5%) farms were located in Otago; 5 (2%) farms were located in West Coast and 1 farm was located in Nelson.

The breakdown of how these OVERSEER farm files (specifically, those deemed suitable for benchmarking) eventually mapped into the revised typology structure is shown in Table 4.1. Fifty one percent of the farms were categorised into "warm" locations and 49% into "cool" (Table 4.1). The 12 typology units selected for detailed mitigation modelling (as described in section 3.5; results presented in section 4.3) and used for benchmarking P losses, accounted for 79% of the total numbers of farm files available, with two of these typologies accounting for 23% of the farms (Table 4.1).

Table 4.1. Breakdown of farms assigned to individual typology units. Note that typologies with no farms present are not listed

Modelled						# farms		OVERSEER file numbers	% of total files
Typology label	Climate	Slope	Drainage	Wetness	Low	ASC Medium	High		
T1	Warm	Flat	Poor	Dry	2	22	14	38	12
T2				Moist	3	14	8	25	8
				Wet				7	2
				Irrigated				1	<1
			Well	Dry				4	1
T3				Moist	3	2	12	17	5
T4				Wet	1	2	13	16	5
			Light	Dry				3	1
				Moist				1	<1
				Wet				1	<1
		Moderate (rolling)	Poor	Dry				1	<1
				Moist				4	1
				Wet				3	1
			Well	Dry				2	1
T5				Moist	2	3	13	18	6
T6				Wet	0	3	10	13	4
				Irrigated				1	<1
			Light	Moist				3	1
				Wet				2	1
T7	Cool	Flat	Poor	Dry	6	8	0	14	4
T8				Moist	5	10	0	15	5

			Wet				3	1
T9			Irrigated	4	8	0	12	4
		Well	Dry				2	1
T10			Moist	3	16	1	20	5
T11			Wet	6	7	12	25	8
			Irrigated				4	1
		Light	Dry				1	<1
			Wet				2	1
T12			Irrigated	16	19	0	35	11
	Moderate (Rolling)	Poor	Dry				5	2
			Irrigated				2	1
		Well	Dry				1	<1
			Moist				2	1
			Wet				6	2
			Irrigated				1	<1
		Light	Dry				1	<1
			Wet				1	<1

4.2 Benchmarking losses

4.2.1 Nitrogen

Whole system N losses to water (hereafter referred to as N_{water}) were estimated to range from 11 to 161 kg N ha^{-1} yr^{-1}. Loss estimates displayed a log-normal distribution with mean and median loss values of 44 and 40 kg N ha^{-1} yr^{-1}, respectively (Figure 4.1). The majority (78%) of farms had N_{water} values of between 20 and 50 kg ha^{-1} yr^{-1}.

The N input-output framework plot for all farms (Figure 4.2, whole-system estimates) shows the broad distribution of farm N efficiencies. These are delineated in terms of 20th and 80 percentile values for NUE (blue lines), N surplus (black lines) and N output in product (red lines). Based on these distributions we can see that most (i.e. 60%) farms had NUE values between 22 and 30%, N surplus values between 125 and 200 kg $ha^{-1}yr^{-1}$ and N outputs in product between 50 and 75 kg $ha^{-1}yr^{-1}$. These NUE and N surplus metrics fall within the lower end of the ranges reported for intensive dairy production systems in Europe, Australia and the US (de Klein et al. 2017a).

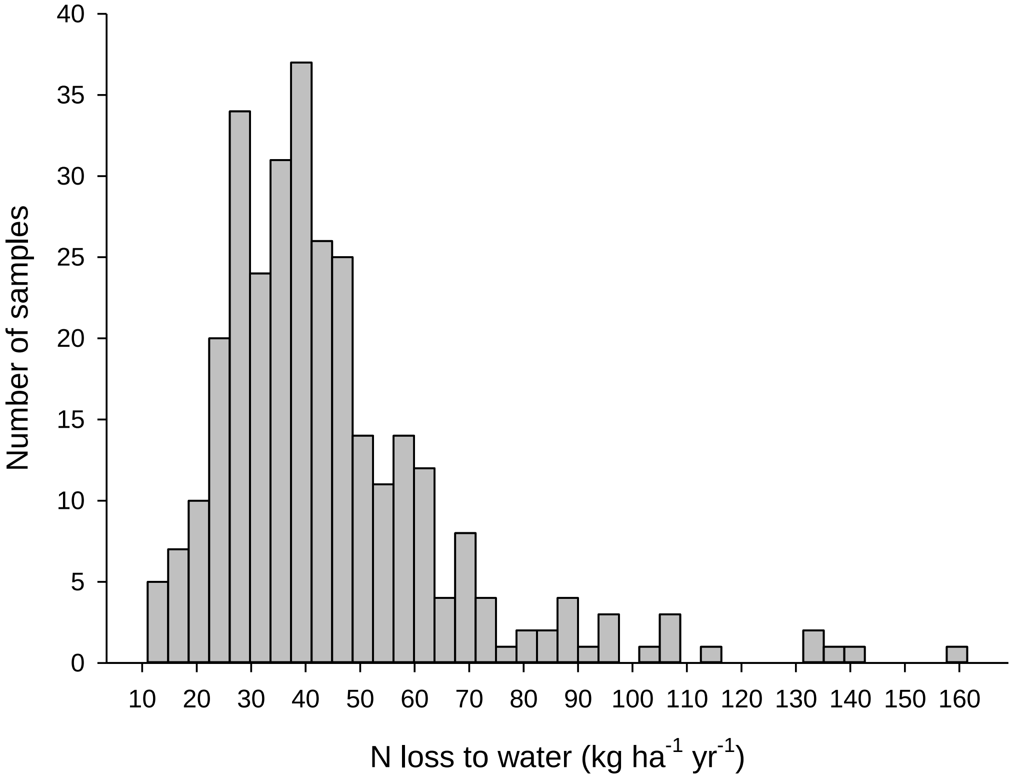

Figure 4.1. Frequency distribution of estimated N losses to water (whole-system) for all farms.

The next step in the benchmarking process was to interrogate the dataset to determine if it was appropriate to derive N leaching efficiency metrics based upon values that were categorised according to typology risk attributes (Table 4.1). Because many typology units contained relatively few (12 or less) farm files, the formal statistical analysis was confined to the 12 typology units (241 farms) that contained 13 or more farms per typology unit. The N metrics considered in this analysis were estimates of N_{water}, NUE, N surplus and a calculation of "commercial N surplus". This latter metric was derived and evaluated as an index of imported N via fertiliser and purchased feed to determine if rates of these imports varied significantly between typology units.

The key efficiency metrics that delineated farms according to typology attributes were N surplus ($P < 0.001$) and N_{water} ($P < 0.001$). Neither NUE ($P = 0.269$) or commercial N surplus ($P = 0.206$) terms were significant overall. More detailed analysis indicated that N surplus values were only significantly different ($P < 0.001$) between irrigated and non-irrigated groups of farms, most probably reflecting the greater imports of purchased feeds and fertiliser onto irrigated farms where any potential water constraint to plant growth has been removed. As hypothesised, soil drainage status and wetness were the two key typology attributes that influenced N_{water}; once these effects were accounted for, there appeared to be no effect of climate *per se* (warm v. cool) on N_{water} values. Slope appeared to have a minor effect on N_{water}: the only significant difference between (equivalent) flat and moderately sloping typologies (44 v 34 kg N $ha^{-1}yr^{-1}$, respectively; $P < 0.05$) was observed for farms located in moist environments and on well-drained soils. Accordingly, the median N_{water} values for the top 10 typology groups that were deemed most useful for benchmarking N_{water} are illustrated using boxplots in Figure 4.3, including 10th, 25th, 75th and 90th percentile values for all farms. Some interesting features of Figure 4.3 are:

- There is a large spread of N_{water} values within any typology group, reflecting the variability and influence of land use pressure i.e. farm inputs and management practices.
- Whilst not clearly evident for Poorly-drained soil groups, the effect of N displacement is readily apparent for Well-drained and Light soils which show significantly greater ($P < 0.001$) values of N_{water} as wetness increases.

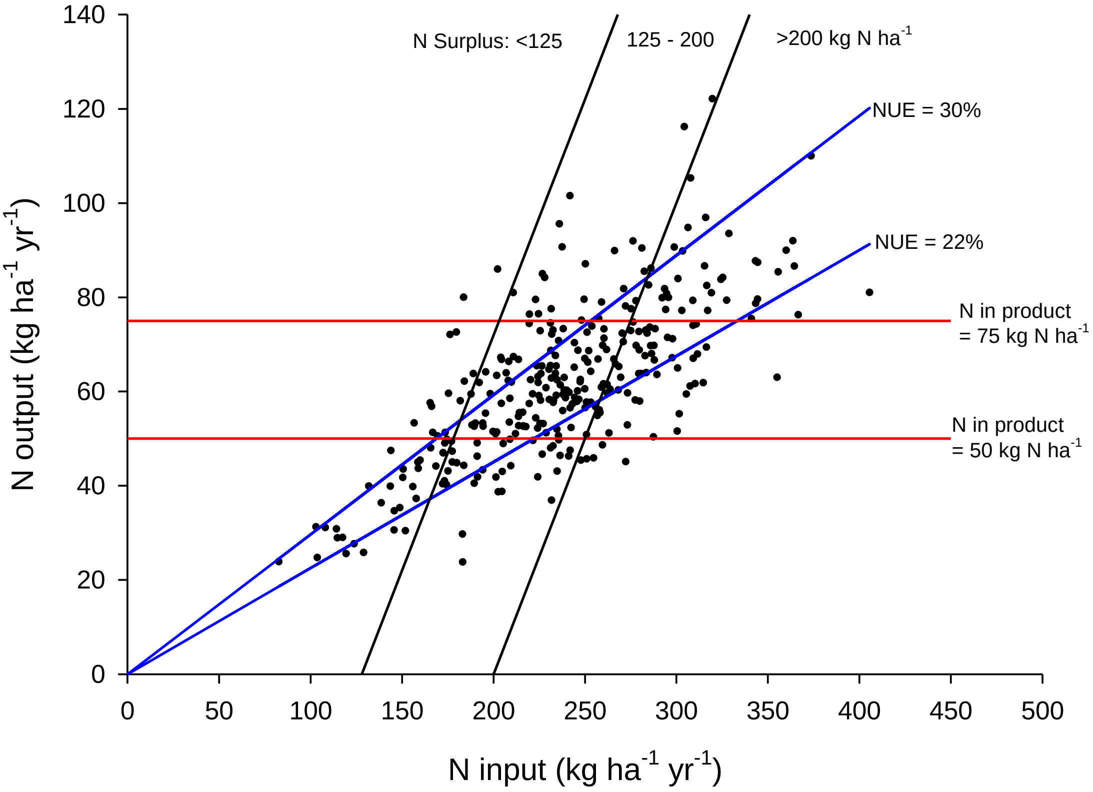

Figure 4.2. Diagram of the whole-system NUE indicator framework for the 309 farms deemed suitable for benchmarking N inputs and losses. The red horizontal lines represent the 20th and 80th percentile values for N removed in product; the diagonal blue lines depict the 20th (NUE = 22%) and 80th (NUE = 30%) percentile values for NUE; and the diagonal black lines represent the 20th (125 kg N $ha^{-1}yr^{-1}$) and 80th (200 kg N $ha^{-1}yr^{-1}$) percentile values for N surplus.

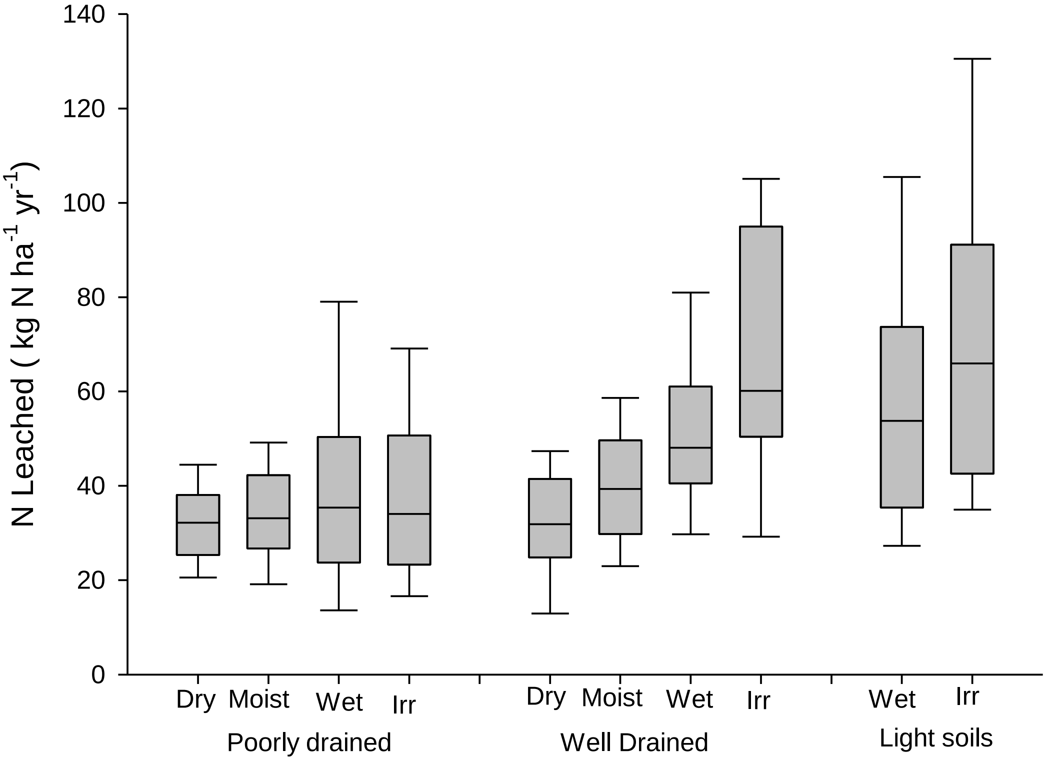

Figure 4.3. Comparison of calculated whole-system N leaching losses from farms with different wetness and drainage attributes combined across temperature and slope classes (n = 309). The top and bottom of the boxes represent the 25th and 75th percentiles, respectively, whiskers represent the 10th and 90th percentiles and the line in the box is the median value.

4.2.2 Phosphorus

There was a wide range in estimated P loss risk values, from 0.32 to 9.34 kg ha^{-1} yr^{-1} with an average loss of 1.3 kg ha^{-1} yr^{-1}. These values are broadly similar to measured P losses previously reported in NZ for dairy sites of varying size and locations, where the range was 0.1 to 10 kg ha^{-1} yr^{-1} with an average loss of 1.9 kg ha^{-1} yr^{-1} (McDowell and Wilcock 2008). More than 85% of farms were estimated to lose < 2 kg P ha^{-1} yr^{-1} (Figure 4.4). Based on the P loss risk assessment index used in OVERSEER, these farms are considered a low to medium risk, with some potential for P loss and a chance for adverse impacts on water quality, depending on the characteristics of the downstream receiving environment (McDowell et al. 2005). By comparison, <4% of farms were estimated to lose > 4 kg P ha^{-1} yr^{-1}, considered an extreme loss risk and a high potential for consequent impairment of water quality.

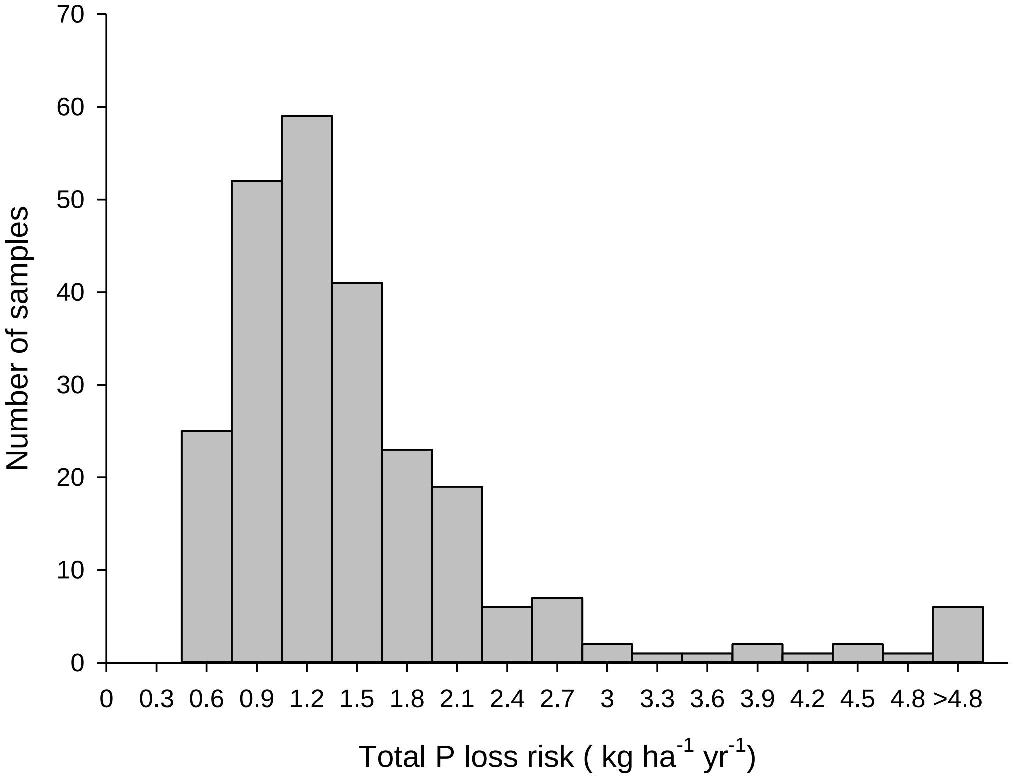

Figure 4.4. Frequency distribution of estimated P loss risk to water (kg ha^{-1} yr^{-1}) from OVERSEER farm file areas (all farms).

Several typology attributes were identified as having a significant effect on the estimated P loss values. These included wetness ($P = 0.047$), ASC ($P < 0.001$), slope ($P = 0.019$) and climate ($P < 0.001$). A comparison of P loss values from farms with different wetness and ASC attributes is given in Figure 4.5. In general, P losses decreased as ASC increased, although much variability is evident within each typology grouping. This reflects findings from research that shows that as soil ASC increases, so does the ability of soil to sorb P, thus reducing its potential to be lost in either overland or subsurface flows (McDowell and Condron 2004). In addition, it was found that the quantity of P lost at sites with low ASC increased for moist and wet typologies. This is consistent with rainfall acting as a key transport driver of P loss, in particular when precipitation exceeds soil infiltration rate and results in overland flow. In contrast, for sites with medium or high ASC, wetness was less important, presumably because of the smaller amount of soluble P potentially available to be lost in runoff. Greater P losses were estimated for sites with moderate slopes (i.e. rolling topography) compared to those that were flat (Figure 4.5). Increasing slope is well recognised as one of the main drivers of P loss from soils, largely via particulate P forms (McDowell et al. 2005).

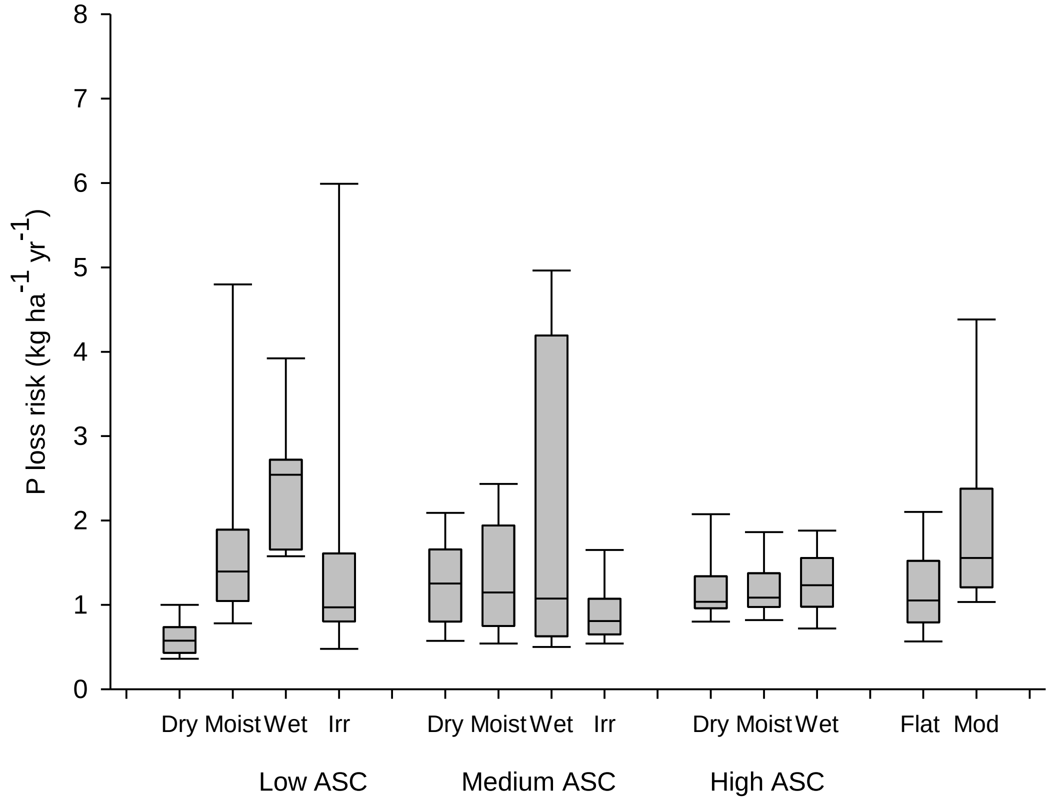

Figure 4.5. Comparison of P loss risk values estimated for farms (OVERSEER farm file areas) with different wetness, soil ASC and slope attributes. The top and bottom of the boxes represent the 25th and 75th percentiles, respectively; whiskers represent the 10th and 90th percentiles and the line in the box is the median value.

4.2.3 Greenhouse gas emissions

Total GHG emissions (CH_4+N_2O) ranged from 3,000 to 21,000 kg CO_2eq. $ha^{-1}yr^{-1}$ (Figure 4.6). Loss estimates displayed a normal distribution with the majority of farms emitting between 6,000 and 11,000 kg CO_2eq. $ha^{-1}yr^{-1}$. These losses are in the same range to those previously reported for NZ dairy systems (e.g. Beukes et al. 2011; Dynes et al. 2011; van der Weerden et al. 2017). The CH_4 emissions typically contributed 75-80% of the GHG emissions.

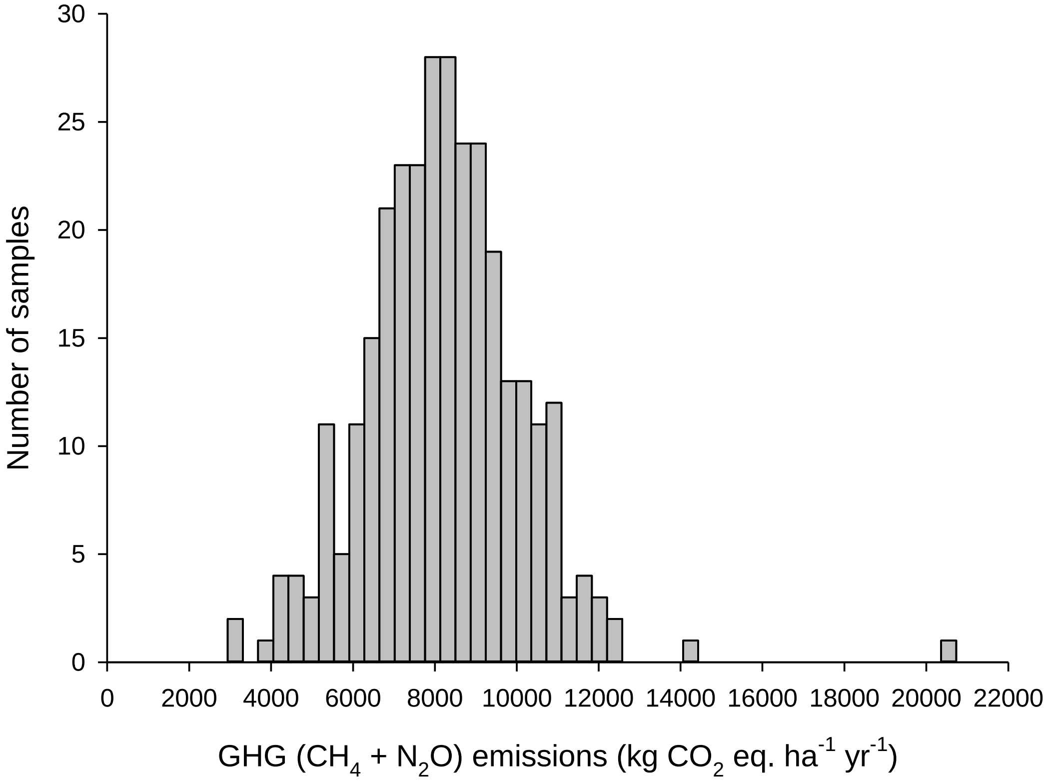

Figure 4.6. Frequency distribution of estimated GHG (CH_4 + N_2O) emissions (whole-system) for all farms.

Climate and wetness attributes significantly affected GHG emissions ($p<0.001$), with greater emissions occurring under warm climates and when farms were irrigated (Figure 4.7). There was a trend of lower GHG emissions on rolling compared with flat land in warm climates, but overall slope did not have a significant effect on GHG emissions (P = 0.29).

Enteric CH_4 emissions are driven by dry matter intake and thus largely by stocking rate (van der Weerden et al. 2017). Soil N_2O emissions are affected by N inputs and cycling, and by soil and climate conditions that affect the proportion of gaseous N lost as N_2O. However, in this study we used the “annual average” emission factors setting in OVERSEER for estimating N_2O emissions (see section 3.4). In our analysis, N_2O emissions are therefore solely driven by N inputs and N cycling due to increased farm intensity and stocking rate. It is therefore not surprising that warm climates and/or irrigation were the key typology features affecting GHG emissions i.e. these highly productive farms produced the greatest amounts of feed supporting higher stocking densities.

Overall then, our analysis suggest that the key benchmarking attributes for GHG emissions are climate (cool vs warm) and irrigation.

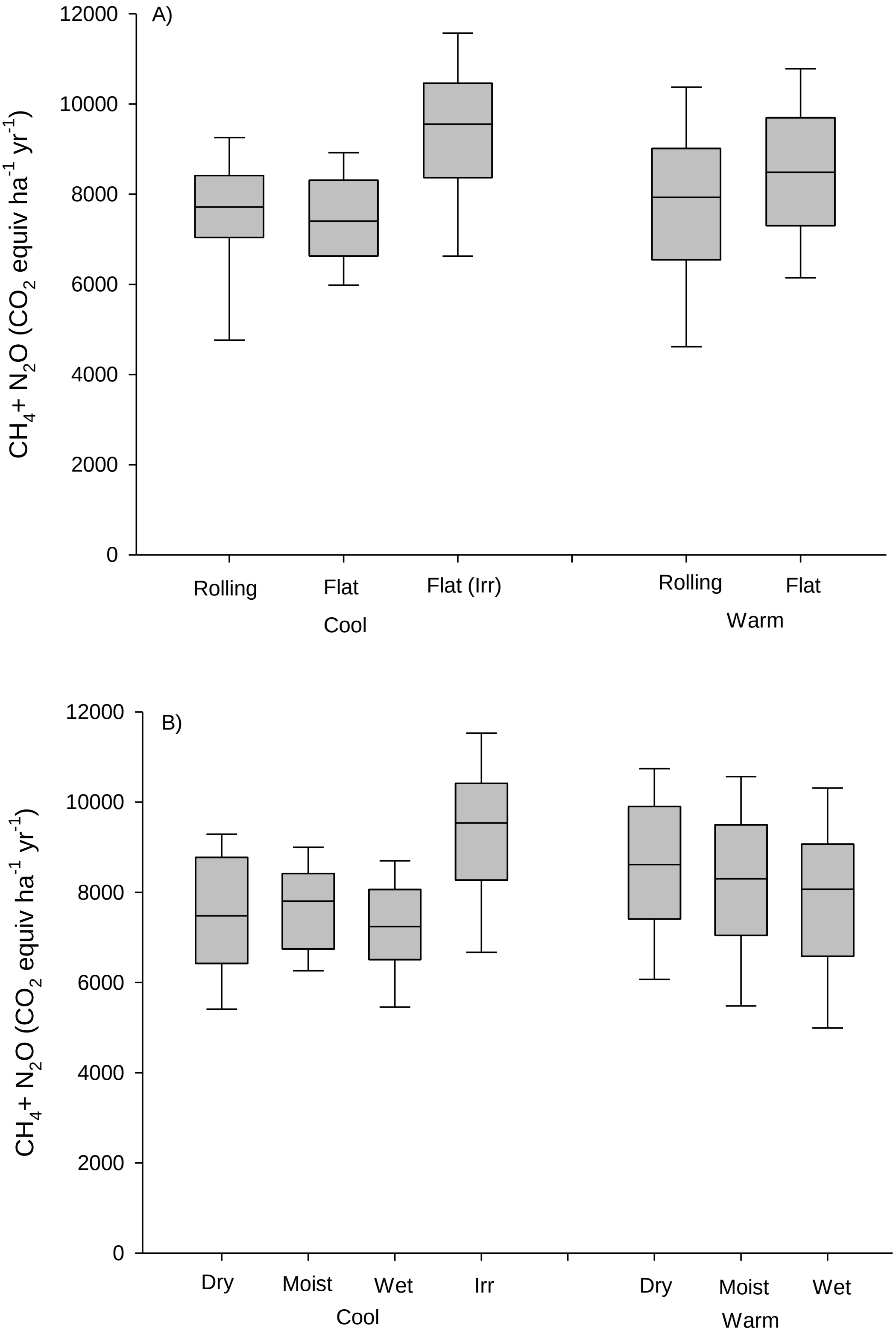

Figure 4.7. Comparison of greenhouse gas losses (whole-system) from farms grouped according to A) climate and contour and B) climate and moisture. The top and bottom of the boxes represent the 25th and 75th percentiles, respectively, whiskers represent the 10th and 90th percentiles and the line in the box is the median value.

4.3 Effectiveness of mitigations

4.3.1 Mitigating N losses

The whole-system N efficiency metrics for each of the key typology groupings illustrated in Figure 4.2 are documented in Table 4.2. As described in section 3.5 (Mitigation Assessments), these metrics and thresholds were used to select those farms that were categorised as either relatively highly efficient (HE) or less efficient (LE) within each typology. The following section documents the modelled effectiveness of a range of mitigation measures that were progressively applied to these HE and LE farms. The hypothesis behind this approach was that greater reductions in N leaching would be achieved for LE farms where N surpluses were greatest and NUE lowest. Other key objectives of this assessment were to (i) determine how far N_{water} could be reduced by the progressive implementation of the selected mitigation measures, and (ii) identify where the greatest reductions in N_{water} could be achieved (and thus where reductions are likely to be most cost-effective).

Table 4.2. Estimates of whole-system N efficiency metrics for farms in key typology groupings. Quoted numbers (kg N $ha^{-1}yr^{-1}$) represent 20th percentile values, median and 80th percentile values, respectively.

Drainage status	Wetness	N input	Product N	NUE	N surplus
		20th, 50th, 80th	20th, 50th, 80th	20th, 50th, 80th	20th, 50th, 80th
Poor	Dry	211, 235, 276	52, 63, 76	23, 26, 30	129, 161, 189
	Moist	192, 234, 280	50, 62, 70	23, 26, 28	131, 150, 189
	Wet	174, 214, 247	43, 51, 66	21, 24, 27	116, 157, 169
	Irrigated	212, 272, 331	51, 67, 80	21, 25, 29	152, 194, 233
Well	Dry	199, 219, 286	59, 64, 81	28, 30, 33	122, 148, 193
	Moist	175, 226, 268	46, 60, 72	24, 26, 30	114 ,154, 190
	Wet	188, 230 ,273	43, 54, 73	21, 25, 29	125, 157, 180
	Irrigated	234, 284, 316	65, 69, 75	22, 26, 29	166, 187, 233
Light soils	Wet	214, 235, 251	50, 57, 59	21, 22, 25	109, 176, 185
	Irrigated	248, 295, 315	62, 74, 88	21, 25, 30	166, 203, 229

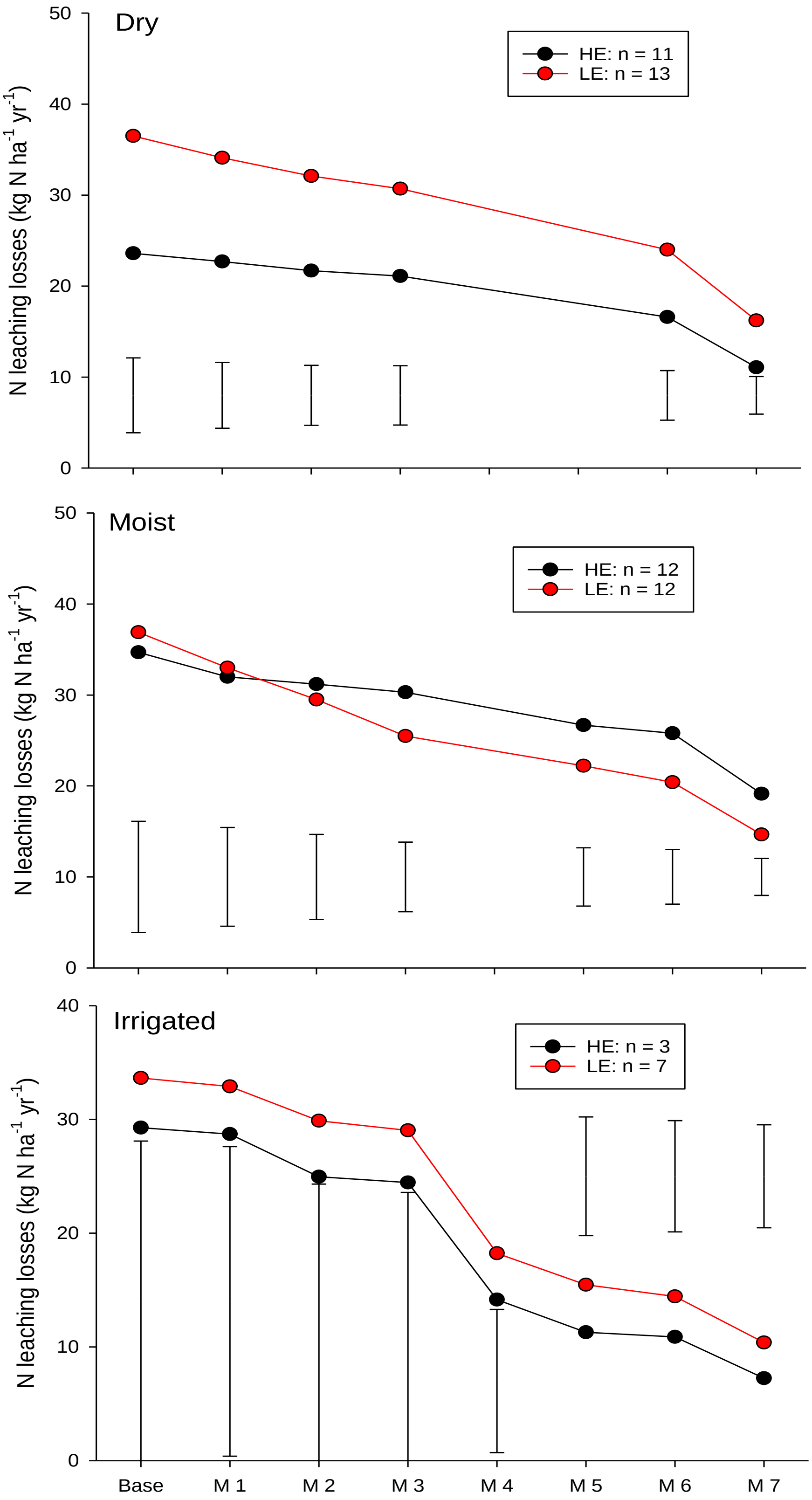

Figure 4.8. The effects of progressive implementation of mitigation measures on N leaching losses (kg N ha^{-1} yr^{-1}) from farms (whole system) on **flat poorly drained** soils located in Dry (T1, T7), Moist (T2, T8) or Irrigated (T9) locations. Error bars indicate LSD$_{0.05}$; HE and LE represent highly and less efficient farms, respectively, as per definitions in section 3.5.1. Farms managed under good, improved or advanced management practice are represented by mitigation bundles M1, M2 - M4 and M5 - M7, respectively.

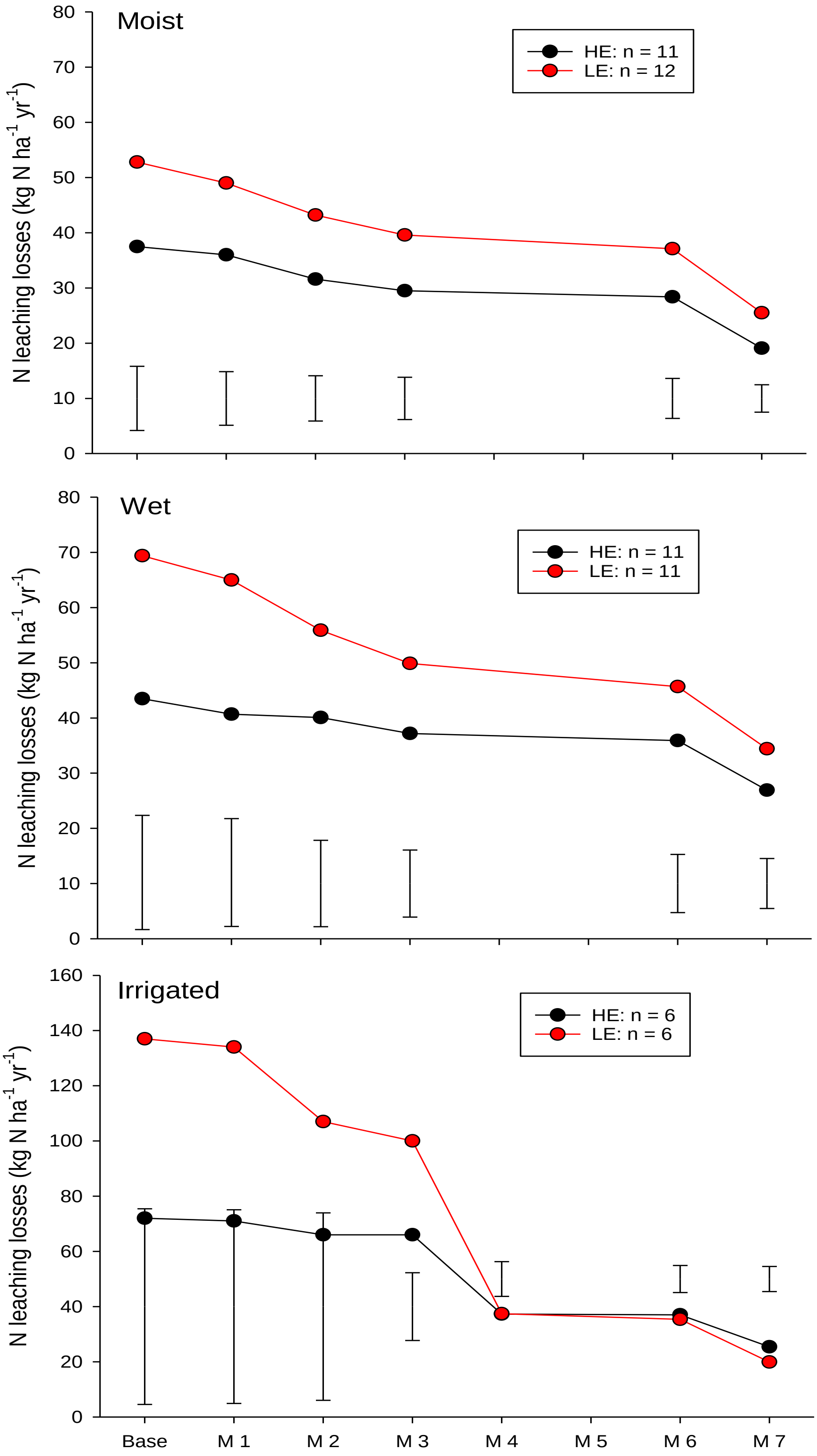

Figure 4.9. The effects of progressive implementation of mitigation measures on N leaching losses (kg N ha^{-1} yr^{-1}) from farms (whole system) located on **flat well drained** (Moist (T3, T10) and Wet (T4, T11) locations) and **light** (Irrigated, T12) soils. Error bars indicate $LSD_{0.05}$; HE and LE represent highly and less efficient farms, respectively, as per definitions in section 3.5.1. Farms managed under good, improved or advanced management practice are represented by mitigation bundles M1, M2 - M4 and M5 - M7, respectively.

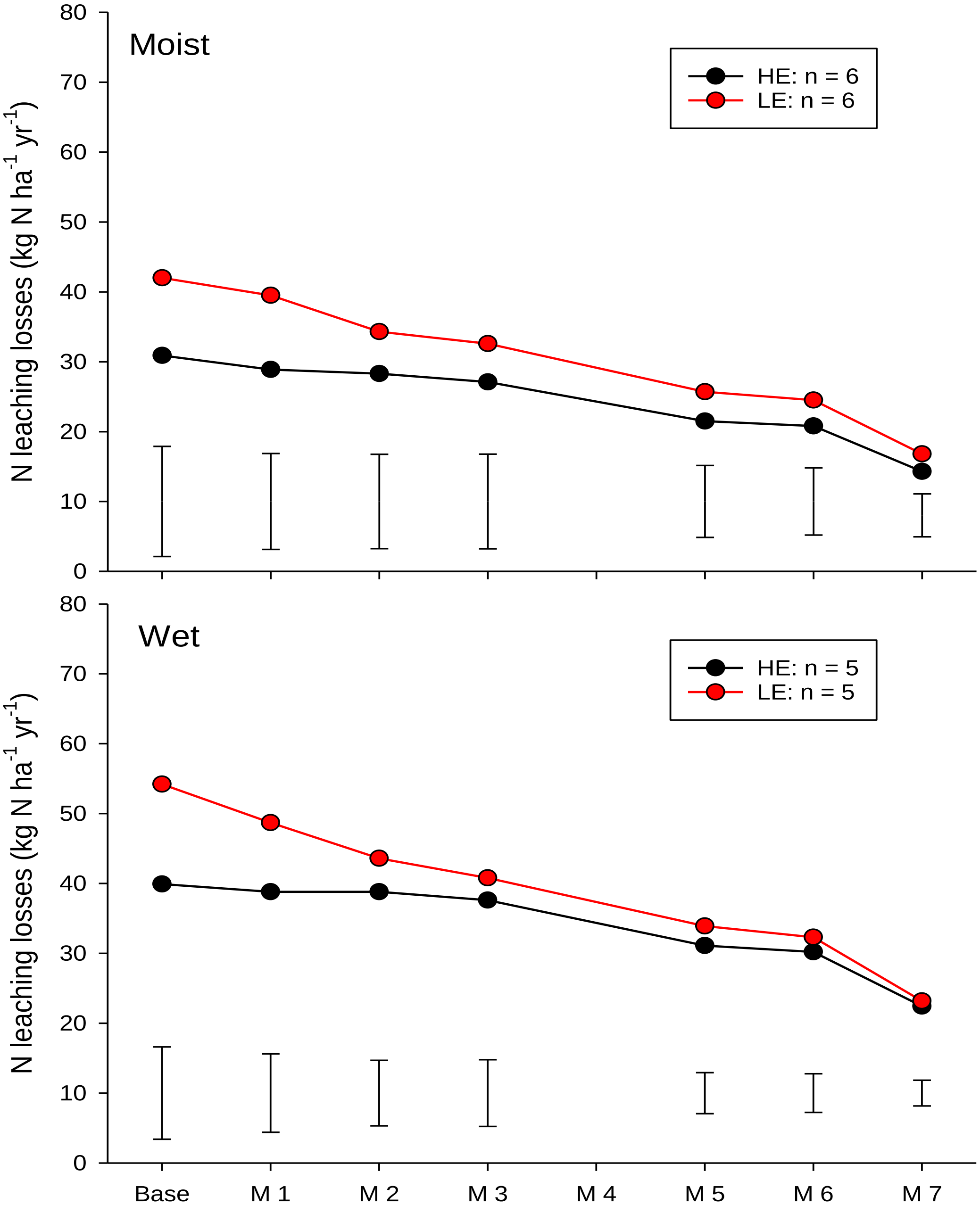

Figure 4.10. The effects of progressive implementation of mitigation measures on N leaching losses (kg N ha^{-1} yr^{-1}) from farms (whole system) on **rolling well drained** soils located in Moist (T5) or Wet (T6) locations. Error bars indicate LSD$_{0.05}$; HE and LE represent highly and less efficient farms, respectively, as per definitions in section 3.5.1. Farms managed under good, improved or advanced management practice are represented by mitigation bundles M1, M2 - M4 and M5 - M7, respectively.

The effects of progressive implementation of mitigation measures to each typology grouping on N_{water} are illustrated in Figures 4.8 – 4.10. In most cases plots of N_{water} were initially greater for LE farms than HE farms but generally converged as mitigation measures were progressively implemented. This general pattern was observed in 7 of the 8 plots presented in Figures 4.8 – 4.10, although in many cases limited sample sizes meant that statistical analysis could not confirm these trends and effects; the general response does however support our initial hypothesis that greater reductions in N leaching can likely be achieved by targeting LE farms where N surpluses are greatest and NUE values are lowest.

The effectiveness of mitigation measures varied between each subset of HE or LE farms and depending on which mitigation bundle was implemented. Improved irrigation practices (M4) were modelled to deliver relatively large reductions in N_{water} for the two key irrigated typology groups (Table 4.3). Excluding this irrigation effect, the mean cumulative reductions in N_{water} for the HE subset of farms were 5, 8, 12, 26, 28 and 47% for the M1, M1-2, M1-3, M1-5, M1-6 and M1-7 mitigation bundles, respectively. Corresponding reductions in N_{water} for the LE subset of farms were 8, 18, 24, 37, 40 and 56% for the M1, M1-2, M1-3, M1-5, M1-6 and M1-7 mitigation bundles, respectively. Averaged across all typology groupings, the largest reductions were achieved for the M7 bundle (off-paddock managements), closely followed by the M5 bundle (wetland enhancement), in both cases for both the LE and HE subsets of farms. Thereafter, the M2 (improved effluent management), M1 (“tidy” farms) and M3 (imported N reduced to the median for that typology) bundles delivered the next largest reductions in N_{water} for the LE farms. Mitigation bundle 6 (imported N reduced to the 25th percentile for that typology) was modelled to deliver the smallest reduction in N_{water} for both the LE and HE farm subsets.

Figure 4.11 illustrates where the greatest reductions in N loads are likely to be achieved in response to the implementation of mitigation measures; corresponding increases in NUE values are shown in Figure 4.12. These figures clearly indicate that the greatest N_{water} load reductions can be achieved for the irrigated farms on Light soils. Well-drained moist and wet typologies are identified as the next set of typology groupings where the greatest reductions in N_{water} can generally be achieved. Improved irrigation practices targeted at the irrigated, poorly-drained typology are also modelled to deliver relatively large reductions in N_{water}. Mitigations applied to the non-irrigated poorly-drained typology groupings have the smallest effect on modelled N_{water} reductions.

The effectiveness of individual mitigation measures were also assessed as part of an associated programme of work funded by the Our Land and Water National Science Challenge (within the Sources and Flows objective). Summary results are presented in Appendix 9.5 as supplementary material to this report.

Table 4.3. The effects of cumulative/progressive mitigation measures M1 – M7 on modelled reductions in whole-farm N losses (% change from base farm) for highly efficient (HE) and less efficient farms (LE) as per definitions in section 3.5.1. Typologies are categorised by drainage (light, poorly- or well-drained soils) and moisture (dry, moist, wet or irrigated (“Irr”)) status; Roll refers to farm typologies on rolling topography.

Typology#		Base (kg N ha^{-1})	M 1	M 2	M 3	M 4	M 5	M 6	M 7
HE farms									
T1 + T7	Poor, Dry	23	4%	8%	11%		28%	29%	53%
T2 + T8	Poor, Moist	25	8%	10%	13%		23%	26%	45%
T9	Poor, Irr	29	2%	15%	16%	52%	61%	63%	75%
T3 + T10	Well, Moist	37	4%	15%	20%			23%	48%
T 4 + T11	Well, Wet	44	7%	8%	15%			17%	38%
T12	Light, Irr	72	1%	8%	9%	48%		49%	65%
T5	Roll, Moist	31	6%	8%	12%		31%	33%	54%
T6	Roll, Wet	40	3%	3%	6%		22%	24%	44%
Mean reduction (Irr excluded)			5%	8%	12%		26%	28%	47%
LE farms									
T1 + T7	Poor, Dry	37	7%	12%	16%		32%	35%	56%
T2 + T8	Poor, Moist	37	11%	20%	31%		40%	45%	60%
T9	Poor, Irr	34	2%	11%	14%	46%	54%	57%	69%
T3 + T10	Well, Moist	53	7%	18%	25%			30%	52%
T 4 + T11	Well, Wet	71	6%	19%	28%			34%	50%
T12	Light, Irr	137	2%	21%	27%	73%		74%	85%
T5	Roll, Moist	42	6%	18%	22%		39%	42%	60%
T6	Roll, Wet	54	10%	20%	25%		37%	40%	57%
Mean reduction (Irr excluded)			8%	18%	24%		37%	40%	56%

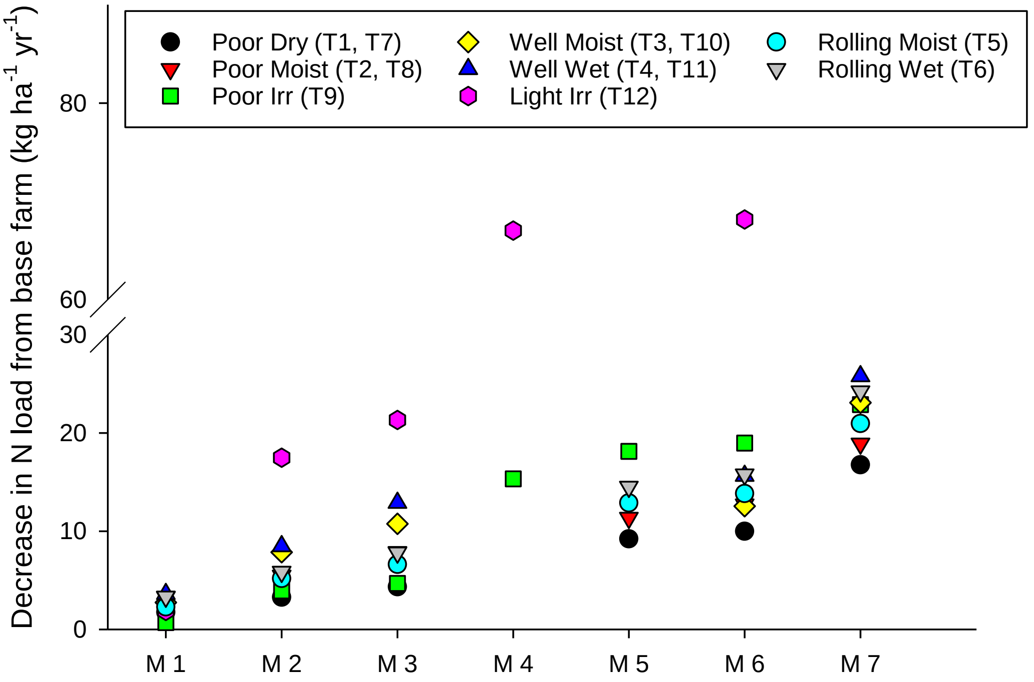

Figure 4.11. Reductions in N leaching (kg N ha^{-1} yr^{-1}; whole-system estimates) resulting from the progressive implementation of selected mitigations measures. Note that Poor, Well, Light and Rolling refer to drainage and contour attributes whilst Dry, Moist and Irr refer to wetness attributes, as defined in section 3.1.

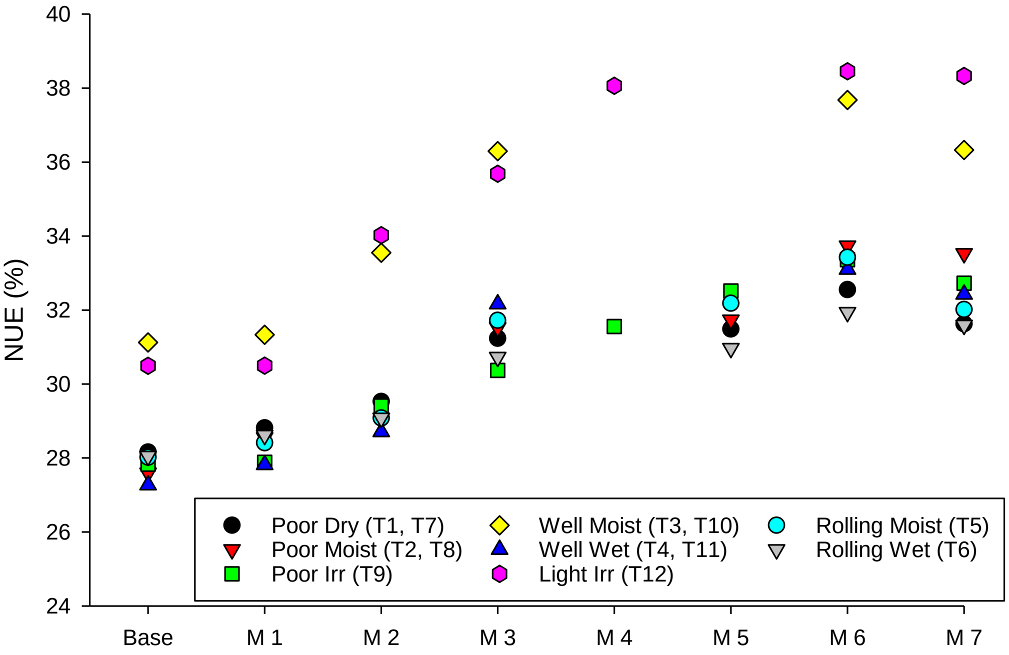

Figure 4.12. Responses in N use efficiency (NUE) resulting from the progressive implementation of selected mitigation measures. Note that Poor, Well, Light and Rolling refer to drainage and contour attributes whilst Dry, Moist and Irr refer to wetness attributes, as defined in section 3.1.

4.3.2 Mitigating P losses

Because our mitigation assessments were undertaken using assumed rather than actual soil P test data for individual farms (refer to section 3.4 for details), caution should be exercised when examining the P mitigation responses discussed below. Findings are nevertheless presented in order to provide information about the likely directions and possible magnitude of changes in P loss due to the implementation of the modelled mitigation bundles. No distinction is made between LE and HE subsets of farms given these were defined based upon N, rather than P efficiency metrics. Note that mitigation responses are again reported for the OVERSEER farm file areas, not the estimated whole-system areas.

The specific effects of lowering soil Olsen P values to agronomically-optimum ranges on P losses are documented in the Appendix; section 9.2. Due to the absence of actual measured soil Olsen P values for most of the available OVERSEER files, this evaluation was undertaken by firstly using soil test information provided by Ballance Agri-Nutrients to estimate “typical” or likely P losses for each region and soil group. These values were then substituted with Olsen P input values that represented the lower end of the agronomical optimal range for each soil group. Based on this approach, reducing the soil Olsen P value to the lower end of the agronomic range resulted in a significant ($P = 0.006$) decrease in the quantity of P loss to water, with an average reduction of 0.24 kg P ha^{-1} yr^{-1} (19%) across all farms and regions (refer to Appendix, section 9.2).

The largest percentage reductions in P loss were observed for the two farm typology groupings where improved irrigation practices were modelled i.e. in response to the implementation of the M4 bundle (Table 4.4). Much of this response can be attributed to the change from border dyke to centre pivot irrigation, resulting in much less removal of P via surface runoff as observed in previous studies (e.g. Monaghan et al. 2009). This measure was estimated to reduce P losses by 24% for farms on poorly drained soils and by 63% for farms on light soils. The large reductions noted for the latter typology grouping may also reflect the effect of less subsurface flow (due to the improved irrigation scheduling assumed in OVERSEER).

The M1 bundle of mitigation measures was modelled to be the next most effective approach to reducing P losses, by 7 – 27%. The largest reductions were observed for farms on rolling topography; proportional reductions were also observed to be greater as farm wetness attributes increased. The main drivers of the observed reductions in P loss within the M1 bundle were reducing soil Olsen P contents to agronomically-optimal levels (as described above and in Appendix 9.2), avoiding applying P fertiliser in high risk months and changing to less soluble forms of fertiliser P for farm blocks located on poorly draining soils or sloping contour.

The improved effluent management practices modelled within mitigation bundle M2 were estimated to reduce P losses by 2 – 12%, with larger reductions observed for farms on rolling compared to flat land. Relatively small reductions in P loss were modelled for mitigation bundle M3 (1 – 4%) which can be attributed to changes in the P contents of imported feeds (mainly replacing PKE with maize, cereal grains or silages with lower P contents). Mitigation bundles M5 and M6 effectively had no effect on P loss, whereas bundle M7 was modelled to actually increase P losses slightly. This increase in loss is attributed to the modelled increased risk of P loss when handling manures and effluents deposited in the off-paddock facilities that were required to implement this mitigation strategy.

The generalised responses documented in Table 4.4 suggest that mitigation bundles M1 to M4 could deliver appreciable reductions in P loss. For the irrigated farm typology groupings, these reductions could be as great as 33 (poorly drained soils) to 63% (Light soils). For non-irrigated soils, reductions of between 15 - 34% are suggested in response to the implementation of mitigation bundles M1 to M3.

Table 4.4. The effects of cumulative/progressive mitigation measures M1 – M7 on model estimates of whole-farm P loss. Typologies are categorised by drainage (light, poorly- or well-drained soils) and moisture (dry, moist, wet or irrigated) status; Roll refers to farm typologies on rolling topography.

Typology[#]		Base farm	M 1	M 2	M 3	M 4	M 5	M 6	M 7
kg P ha^{-1} $year^{-1}$									
T1 + T7	Poor, Dry	1.10	1.02	0.97	0.94		0.93	0.91	1.03
T2 + T8	Poor, Moist	1.31	1.16	1.14	1.11		1.09	1.08	1.17
T9	Poor, Irr	0.93	0.88	0.86	0.84	0.62	0.61	0.60	0.62
T3 + T10	Well, Moist	1.28	1.19	1.12	1.07			1.06	1.13
T 4 + T11	Well, Wet	1.61	1.37	1.31	1.26			1.26	1.33
T12	Light, Irr	1.70	1.70	1.67	1.64	0.64		0.64	0.66
T5	Roll, Moist	2.41	1.99	1.69	1.64		1.61	1.60	1.78
T6	Roll Wet	2.29	1.67	1.55	1.51		1.49	1.48	1.59
% change (decrease) from base farm									
T1 + T7	Poor, Dry		7%	12%	15%		16%	17%	7%
T2 + T8	Poor, Moist		11%	13%	16%		17%	17%	11%
T9	Poor, Irr		5%	8%	9%	33%	34%	36%	33%
T3 + T10	Well, Moist		7%	12%	16%			17%	11%
T 4 + T11	Well, Wet		15%	19%	21%			22%	18%
T12	Light, Irr		1%	2%	4%	63%		62%	61%
T5	Roll, Moist		18%	30%	32%		33%	34%	26%
T6	Roll, Wet		27%	33%	34%		35%	35%	31%
Mean reduction (Irr excluded)			14%	20%	22%		24%	24%	17%

[#] Poor, Well and Light terms denote poorly-drained, well-drained and Light soils, respectively; Roll refers to farms on rolling topography; and Irr refers to irrigated farms.

4.3.3 Mitigating greenhouse gas emissions

We compared the reduction in N leaching due to the implementation of the mitigation bundles with the reduction in GHG emissions (Figure 4.13). There was a general trend of reductions in GHG emissions increasing with reductions in N leaching losses, especially when mitigation 7 was excluded (Figure 4.13B). As this mitigation is the off-paddock management option, GHG emissions can increase due to greater losses that are expected from housing systems. However, even without mitigation 7, there are farms where N leaching losses decrease, while GHG emissions increased, thus indicating that N leaching mitigation does not necessarily represent a win-win with GHG mitigation. Further analysis of this data may be warranted to investigate the farm and/or management characteristics under which win-wins are most likely. Nevertheless, for irrigated farms on light soils significant reductions in N leaching were achieved with corresponding reductions in GHG emissions (Figure 4.13).

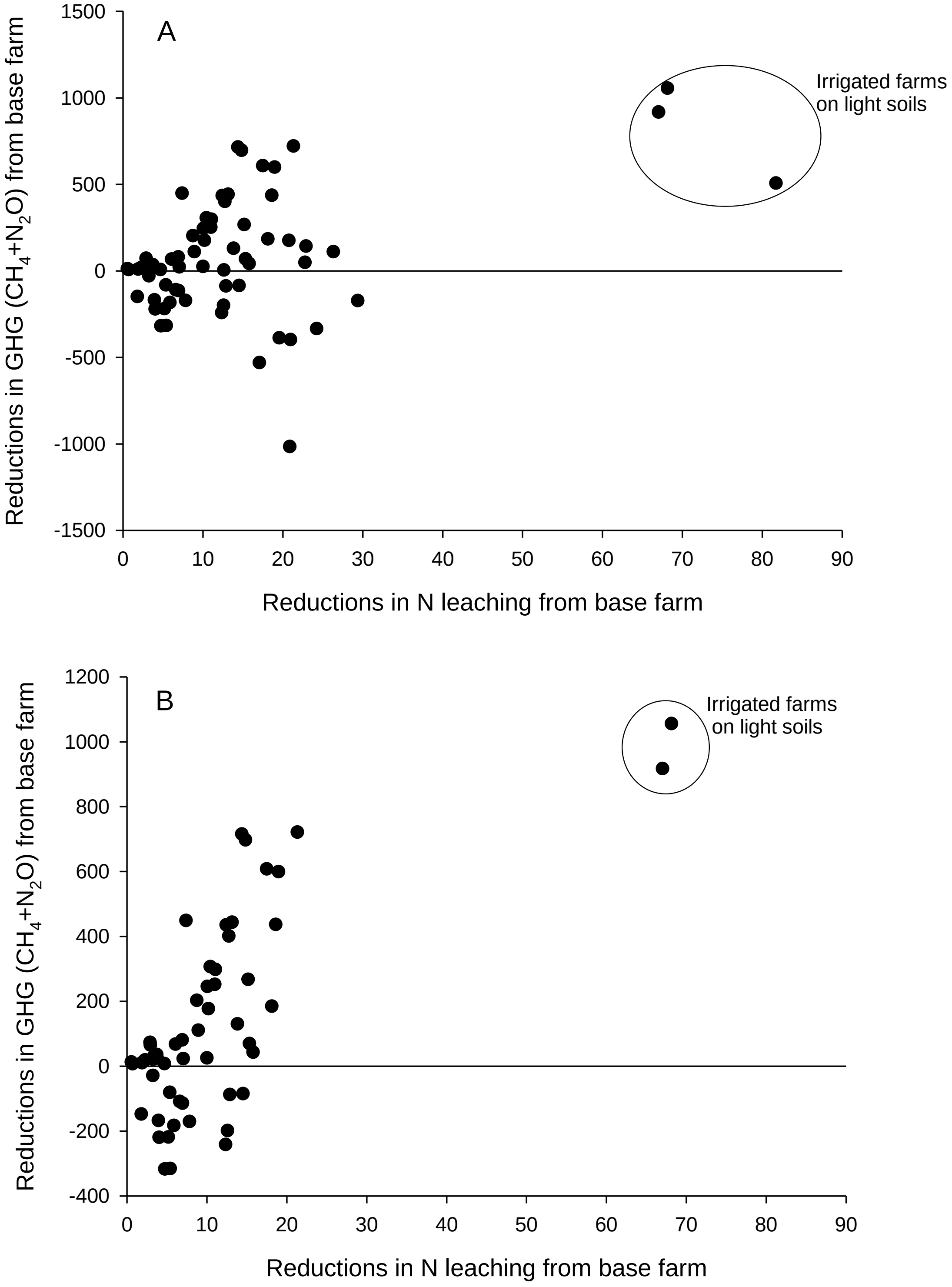

Figure 4.13. Relationships between reductions in (whole system) N leaching losses and reductions in greenhouse gases (GHG) due to the implementation of (A) all mitigation measures, or (B) measures 1 to 6.

5. Discussion

5.1 Benchmarking approaches

Our assessments indicate that we can define benchmarks of N and P losses to water and GHG emissions to air that consider the inherent loss risks caused by landscape and climate vulnerability features. Such an approach would potentially provide an improved set of metrics that could be used as points of reference for farms, thus helping to make assessments of environmental performance more relevant to individual farming circumstances. The attributes used to define these benchmarks do however differ depending on the issue of concern. For N, we suggest that there could be up to 10 key typology groupings that consider soil drainage status and wetness as defining attributes, as illustrated in Figure 4.2. Given the similar median values of N_{water} for poorly drained soil typology groupings evident in Figure 4.2, consideration could be given to amalgamating these, thus reducing the number of key N typologies to 7:

- Poorly drained soils
- Light soils:
    - Irrigated
    - Other (predominantly Wet)
- Well-drained soils:
    - Dry
    - Moist
    - Wet
    - Irrigated

For GHG, there could be up to 7 key typology groupings that consider winter temperature, irrigation and topography as defining attributes, as illustrated in Figure 4.7. Given the broadly similar median values for Dry, Moist and Wet typology groupings (Figure 4.7B) and the variability evident within each typology group, consideration could be given to amalgamating these categories, thus reducing the number of key GHG typologies to 4:

- Irrigated farms
- Non-irrigated farms in winter warm areas:
    - Flat
    - Rolling
- Non-irrigated farms in winter cool areas (Flat and Rolling combined)

Distinguishing key typologies that provide more meaningful benchmarks of farm P losses is less obvious than observed for N_{water} and GHG. The typology attributes identified as having a significant effect on P loss were ASC, climate, slope, and wetness, although again much variability is evident within each of the typology groupings shown in the distributions plotted in Figure 4.5. Given the broadly similar median values for soils categorised as having Medium or High ASC values (Figure 4.5) and the variability evident within each of these typology groups, consideration could be given to amalgamating these categories, thus reducing the number of key P typologies to 6:

- Low ASC soils:
    - Dry
    - Moist
    - Wet
    - Irrigated
- Other soils:
    - Flat
    - Rolling

Based on the typologies suggested above, some possible benchmark ranges for N, P and GHGs are suggested in Table 5.1. These represent the 25th, median and 75th percentile values for each of the key typologies groupings suggested above and have been calculated using results from all 309 Dairybase farm files that were deemed acceptable (refer to Appendix 9.1). A similar set of metrics is provided in Appendix 9.6 based upon the farm units represented by the OVERSEER farm files provided from Dairybase; these metrics may be helpful to modelling initiatives where spatially-discrete estimates of N and P losses to water are required (e.g. the Our Land & Water National Science Challenge).

5.2 Mitigation of N and P losses to water

The mitigation responses evident for LE and HE farms in Figures 4.8 to 4.10 indicates that the N efficiency approach described by the EU Nitrogen Expert Panel (2015) appears to be an effective approach for identifying and mitigating farms where land use pressures are greatest. This showed that greater reductions in N_{water} can likely be achieved by targeting LE farms where N surpluses are greatest and NUE values are lowest. Overall reductions in N_{water} for non-irrigated farms were between 25 – 37% without the use of off-paddock strategies. These reductions are however premised on the implementation of a very broad suite of measures. Inclusion of more costly off-paddock management systems to the suite of mitigation measures could reduce N_{water} values by 47% (HE farms) or 56% (LE farms). Modelling analysis also indicated that relatively large reductions in N_{water} could be achieved if improved irrigation management practices were implemented, such as changing to centre-pivot irrigation or using soil moisture monitoring to improve irrigation scheduling. This effect was particularly apparent for the Light, irrigated typology group.

Table 5.1. Suggested benchmark ranges for N and P losses to water (kg $ha^{-1}yr^{-1}$) and GHG emissions to air ($CO_{2eq.}$ $ha^{-1}yr^{-1}$) as defined by median and 25th and 75th percentile values for each of the identified key typology groupings (309 farms in total). Note that N and GHG ranges are for the whole farm system, whereas P ranges are for OVERSEER farm file areas only.

Issue	Primary typology attribute	Secondary typology attribute	Median value	25th, 75th %iles.
N	Poorly-drained soils	All	33	27, 41
	Light soils	Irrigated	69	45, 91
		Other	42	36, 55
	Well-drained soils	Dry	29	25, 38
		Moist	39	29, 48
		Wet	47	41, 60
		Irrigated	60	54, 87
GHG	Irrigated farms	All	9536	8527, 10371
	Non-irrigated: Winter warm	Flat	8488	7388, 9684
		Rolling	7931	6703, 9009
	Non-irrigated: Winter cool	All	7441	6710, 8291
P	Low ASC	Dry	0.57	0.43, 0.68
		Moist	1.40	1.05, 1.83
		Wet	2.54	1.98, 2.67
		Irrigated	0.93	0.92, 1.60
	Other soils	Flat land	1.05	0.80, 1.47
		Rolling	1.42	1.21, 1.89

The P responses documented in Table 4.4 suggest that mitigation bundles M1 to M4 could deliver appreciable reductions in P loss. For the irrigated farm typology groupings, these reductions could be as great as 33 (poorly drained soils) to 63% (Light soils). For non-irrigated soils, reductions of between 15 - 34% are suggested in response to the implementation of mitigation bundles M1 to M3. Reducing soil Olsen P to the lower end of the agronomic range was modelled to result in a significant decrease (19%) in P losses to water. Findings from the P mitigation analysis do however need to be treated with some caution given they are based on soil test information derived at a regional rather than farm level. Modelled responses do however indicate the likely directions and possible magnitude of changes in P loss due to the implementation of the various mitigation measures that were considered.

Fortuitously, many of the mitigation measures targeting N or P reduction also resulted in some level of reduction in GHG emissions (Figure 4.13). Reductions in N_{water} and greater GHG emissions were noted to occur in some instances however, thus indicating that N leaching mitigation does not always represent a win-win scenario in terms of co-benefits for GHG mitigation. Mitigation bundle 7 in particular was observed to increase GHG emissions due to the increased losses that are expected from housing systems.

5.3 Assessments of reductions in sediment loss risk

The key typology attributes that were deemed to most influence sediment loss were those that influenced surface erosion, namely slope, wetness and soil drainage. Typologies were therefore initially grouped into these 3 main categories for assessments of mitigation effectiveness. Preliminary analysis showed that the effect of wetness was inconsistent, however, and consequently two main typology groups (slope x soil drainage) were used for the assessments reported in Table 5.2. Full details of the inventory approach that was taken and the assumptions used for assessing mitigation effectiveness can be found in Appendix 9.8.

A key message from Table 5.2 is that stock exclusion from streams (one of the actions modelled within the M1 bundle of measures) is likely to be the single most effective measure for reducing sediment loss risk from dairy farms on flat land or well-drained rolling land. This message is generally well recognised by stakeholders, particularly for farms on flat well-drained land where the potential for surface erosion is relatively low (and consequently stream bank erosion can represent a relatively high proportion of farm-scale losses). The next most effective measure would appear to be off-paddock grazing managements (M7) to protect soils from treading damage, which was estimated to reduce sediment losses by between 17% (well-drained soils) to 37% (poorly drained hill land). Strategic grazing of winter forage crops (M1) and wetland attenuation (M5) were each estimated to reduce sediment losses by between 7 – 20%. Preventing laneway runoff into streams was estimated to have a very minor effect on reducing farm-scale discharges of sediment.

Table 5.2. Assessments of likely or possible reductions (%) in sediment losses from key farm typology groupings in response to the implementation of selected mitigation measures. Stock exclusion scenario compares the change (reduction) in estimated sediment loss risk between a farm without or with full stock exclusion from stream margins; remaining mitigation scenarios estimate reductions from a base farm that is assumed to have full stock exclusion from streams.

Bundle	Measure	Flat land		Rolling land	
		Poorly drained	Well drained	Poorly drained	Well drained
M1	Stock exclusion from streams	35 - 50	50 - 76	13 - 20	30 - 40
	Strategic grazing of winter crops	7 – 10	20	15	20
	Prevent laneway runoff	1	1-4	<1	1
M5	Wetland capture	20	0	20	20
M7	Off-paddock mgmt.	16 – 25	17	37	17

5.4 Qualitative assessments of reductions in faecal loss risk

Qualitative assessments of reductions in FMO losses in response to the implementation of mitigation measures were also sought as part of the analysis undertaken in this study. Unfortunately there are no tools available that can be used for this type of analysis where farm-scale assessments are required. Based on our present state of knowledge about *E. coli* cycling and transfers from soil to water, there is a considerable degree of uncertainty associated with estimates of both faecal yields from contrasting land uses (e.g. sheep v. dairy) and the effectiveness of specific mitigation measures. For example, a recent literature review of international data that document the effectiveness of stream fencing for reducing *E. coli* concentrations identified studies where effectiveness ranged from 0 to 97% (Muirhead 2017). Consideration of base-flow and storm-flow stream conditions (Muirhead 2015) and the existence of 4 different numeric metrics that exist for defining “swimability” (Clean Water 2017) are factors that further complicate any analysis and interpretation of mitigation effectiveness. Because of this complexity, current modelling analyses tend to apply broad-brush assessments of mitigation effectiveness at national or “super region” scales (Muirhead 2017).

Given the above uncertainties and complexities, expert opinion was sought as an alternative approach to populate the assessments of FMO reductions that are documented in Table 5.3. These should be treated as qualitative assessments and cannot be used for translation into numeric reductions in faecal loads to water.

Table 5.3. Qualitative assessments of likely or possible reductions in FMO losses from key farm typology groupings in response to the implementation of selected mitigation measures. As documented for P loss assessments, typology groupings are categorised by drainage (light, poorly- or well-drained soils on flat land) and topography attributes; Rolling refers to farm typologies on rolling topography.

Bundle	Measure	Poorly drained	Well drained	Light soils	Rolling land
M1	Stock exclusion from streams	High	High	High	High
	Strategic grazing of winter crops	High	Medium?	N/A	High
	Eliminate stream crossings#	High	High	High	High
	Prevent laneway runoff#	High	High	High	High
	Manage runoff around gates and troughs				
M5	Wetlands?	High?	Medium?	N/A	High?
M7	Off-paddock mgmt.	High	Medium	Low	High

#rated highly effective due to timing considerations (high impact during conditions of low summer flows).

6. Conclusions

Our analysis suggests that consideration of landscape vulnerability factors, such as soil, topography and climate attributes, can be a useful approach for benchmarking contaminant losses to water, and greenhouse gas (GHG) emissions to air, from New Zealand (NZ) dairy farming systems. Some advantages of this approach are that it can be used to assess the relative importance of management versus inherent landscape risk factors on contaminant losses. It also allows for a more targeted approach to selecting mitigations that are appropriate (and most cost-effective) for a particular typology. Considerable variability was observed for N and P losses and GHG emissions within most typology categories and/or groups, reflecting the wide variation in land use pressure caused by contrasting management practices, such as varying levels of farm inputs of feed and fertiliser and/or different grazing systems practiced by farms. Assessments of mitigation measures targeting N losses to water indicated that appreciable reductions could be achieved if a broad suite of measures was implemented, albeit some (such as the M6 & M7 measures) are likely to incur significant cost. Consideration of whole-system N efficiency metrics for each particular typology grouping appears to be a useful approach for guiding mitigation measures, with greater reductions in N leaching estimated for farms where N surpluses were greatest and NUE values were lowest. Whilst most of the mitigation measures were estimated to deliver reductions in N, P and GHG losses, the use of off-paddock facilities (M7) was noted to lead to increases in the latter.

7. Acknowledgements

Ballance Agri-Nutrients generously provided a very detailed dataset of soil Olsen P test values that were categorised by region. The support of Mark Neale and Rachael Davidson (DairyNZ) in providing OVERSEER farm files from Dairybase to the AgResearch modelling team is gratefully acknowledged. The many farmers who dedicated time and energy to constructing these files are also gratefully acknowledged for their support.

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9. Appendices

9.1 Detailed criteria used to assess the quality of OVERSEER farm files

Detailed criteria considered when assessing file quality and deciding whether farms should be retained for analysis were:

- Nutrient budgets are available.
- Farms are not duplicated, i.e. there are not two or more farm files describing the same farm in the same year with differing management policies.
- Milk production and pasture production values estimated by OVERSEER are realistic.
- Description of cows and replacements are internally consistent and the milking herd’s monthly numbers represent cows on farm that were milked during the year, not just those cows milked that month.
- The milking herd’s replacement rate is realistic, e.g. on some farms it looked as if support blocks were grazing replacements and cows from more than one milking platform. On some farms replacement herds were entered twice.
- The age of replacements was realistic, e.g. not 56 months.
- The wintering-off policy is sensible, e.g. one farm with cows only wintered off in May was excluded.
- When cows are in a barn, the hours per day spent on pasture each month is realistic, i.e. not recorded as time in barn (the complement of 24 hours).
- On high production systems supplements are made and/or imported.
- Fertiliser inputs exist when estimated pasture production is high.
- Soils on all blocks are described using either a soil sibling or series.
- All blocks without a measured Olsen P value must be in a region with a soil group for which an average estimate of Olsen P is available.
- Blocks with well drained soils must not have artificial drainage.
- Liquid effluent is not exported.
- The effluent management system is realistic e.g. effluent is not applied from a sump using low rate application methods to blocks with easy hill topography, effluent application is not restricted to one month of the year.
- The description of irrigation management settings is realistic, e.g. on one farm it looked as if information had been entered to ensure the amount of irrigation was minimal.
- Pasture production on irrigated blocks is greater than that of dryland blocks.
- All forage crops and cut and carry crops with an end date are defoliated at least once.
- No significant farm system changes from year to year, e.g. all crops sown out of permanent pasture and none grazed during the reporting year.

9.2 The effects of reducing soil Olsen P concentrations on P losses to water

9.2.1 Background

It is well accepted that P is an essential nutrient for profitable pasture and animal production (Edmeades et al. 2006). In response, research over many years has been undertaken to determine the agronomic optimum soil P test value (i.e. Olsen P) for maximum pasture yield for different agricultural systems, including dairy. At present, there is a recommended range of Olsen P values depending on farm system and soil type i.e. 20-30 mg L^{-1} for sedimentary and volcanic soils and 35-45 mg L^{-1} for Pumice and Organic soils for dairy systems.

It is increasingly reported that in some circumstances P loss from soil to water via surface runoff or subsurface flow is occurring and having a negative impact on water quality. The magnitude of P loss is generally proportional to the soil P concentration. Thus maintaining an Olsen P value within the recommended optimal range is advocated by industry to minimise P loss to water bodies as well as preventing any unnecessary waste of the P inputs to soil.

However, research is also showing that maintaining an Olsen P within the optimal range may not in all instances prevent P loss from soil occurring in concentrations that may negatively affect water quality. This is especially likely for soils with low anion storage capacity or if the soil is saturated with P.

Given that the magnitude of P loss is generally proportional to the amount of P in the soil, a strategy to reduce P loss may be to simply recommend to landowners Olsen P values in soils at the lower end of the optimal range (e.g. 20 rather than 30 mg L^{-1} for sedimentary soils). However, at present there is little data available to support the idea that reducing soil Olsen P from the upper end of the recommended agronomic range to the lower end will decrease P loss to water.

The aim was therefore to determine the quantity of P that can be mitigated by reducing the soil Olsen P to the lower end of the agronomic range and identify which landscape and climatic features this strategy is likely to deliver the greatest benefit.

9.2.2 Method

Using the same farm files that were analysed for benchmarking P loss, an estimate of the quantity of P loss that could be reduced after substituting farm Olsen P data with a value that represented the lower end of the agronomical optimal range was undertaken for each soil group. The agronomical optimal ranges used were based on values reported in Roberts and Morton (2016), with the exception of the Podzol soil group which was instead taken from Edmeades et al. (2006) (Table 9.1).

Table 9.1. The Olsen P values used in the mitigation scenarios.

Soil group	**Olsen P value**
Volcanic	20
Pumice	35
Sedimentary Recent/YGE/BGE	20
Podzol	25
Peat	35

Statistical analysis

Data were checked for normality before ANOVA to determine differences in the quantity of P loss between typologies and *t* tests were conducted to determine the effect of reducing Olsen P on P loss.

9.2.3 Key findings

Across all sites, reducing the soil Olsen P value to the lower end of the agronomic range resulted in a significant (P = 0.006) decrease in the quantity of P lost to water, with an average reduction of 0.24 kg P ha^{-1} yr^{-1} (19%). A significant decrease in P loss was found in four of the 12 typologies (Table 9.2).

Table 9.2. Comparison of the quantity of P lost to water (kg ha^{-1} yr^{-1}) for each farm typology before and after reducing soil Olsen P input values for each farm

Typology*	**P loss**	**P loss**	***P* value**
	Actual	Reduced	
T1 WFPD	1.34	1.08	0.052
T2 WFPM	1.43	1.04	**0.007**
T3 WFWM	1.19	0.93	0.086
T4 WFWW	1.23	0.88	**0.013**
T5 WMWM	1.37	0.99	**0.017**
T6 WMWW	1.45	1.05	**0.004**
T7 CFLI	1.63	1.49	0.777
T8 CFPI	0.99	0.83	0.297
T9 CFPD	0.67	0.60	0.455
T10 CFPM	1.05	0.90	0.230
T11 CFWM	1.05	0.87	0.304
T12 CFWW	1.08	0.85	0.102

*A full description the attributes of each typology are given in section 3.2. Climate is either warm (W) or cool (C); topography is either flat (F) or moderately sloping/rolling (M); drainage status is either poorly- (P) or well- (W) drained or representing a light (L) soils; wetness is dry (D), moist (W), wet (W) or irrigated (I).

There were also significant differences in the quantities of P lost between typologies (Figure 9.1). The average reductions in the quantities of P lost ranged from 0.07 kg ha^{-1} yr^{-1} to 0.40 kg ha^{-1} yr^{-1}.

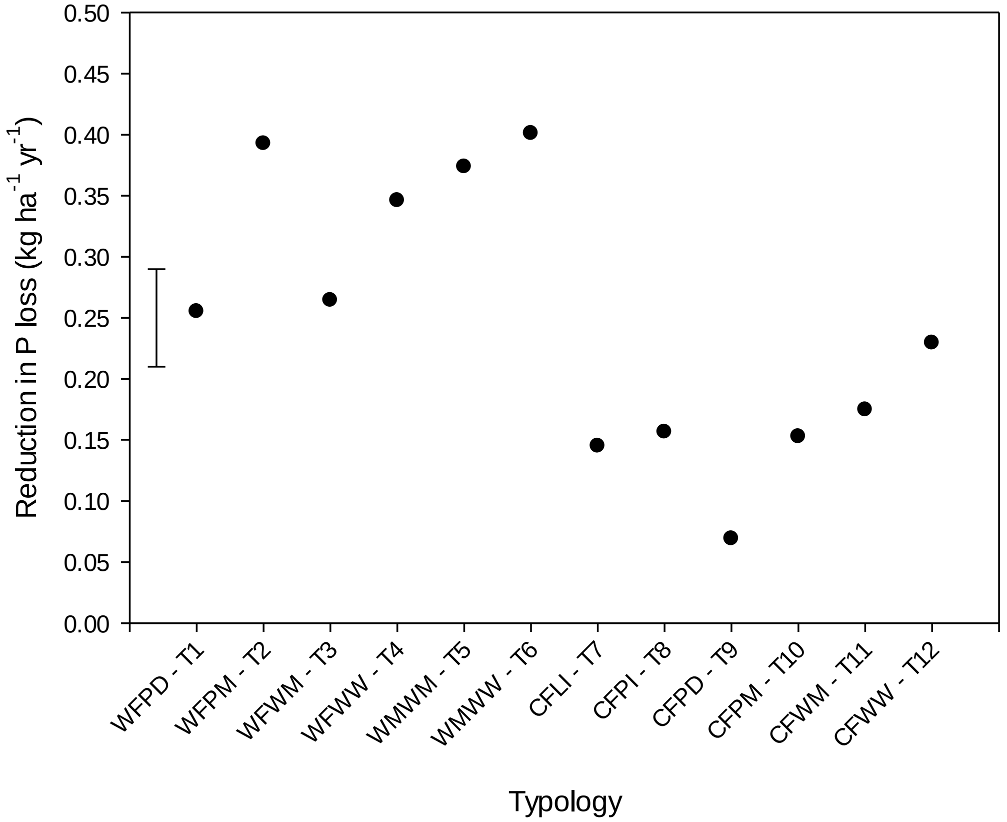

Figure 9.1. Average reductions in P loss (kg ha^{-1} yr^{-1}) for each typology as a result of decreasing soil Olsen P concentrations to the lower end of agronomic ranges. The least significant difference at the *P* = 0.05 level is shown as an error bar for the comparison of average values between typologies. Note Climate is W = warm; C = cool: Topography is F = flat; M = moderate: Drainage is P = poor; W = well; L = light: Wetness is D = dry; M = moist; W = wet; I = irrigated.

The greatest reductions in the quantities of P lost were found for typologies with warm climates, but were either wet or moist, had both flat and moderate slopes, and were dominated by soils with either medium or high ASC. The greater reduction in P loss from typologies with warm compared to cool climates may simply be because overall the warm typologies had greater quantities (average 0.3 kg P ha^{-1} yr^{-1}) of P loss to mitigate. In comparison, the smallest reductions in the quantities of P lost were found for typologies in cool climates that were flat, but were either irrigated, moist or dry with medium and low ASC categories.

Based on the results of this analysis, some sites may respond to a reduction in soil Olsen P concentration. The mean reduction in the quantity of P loss is modest (i.e. <0.40 kg P ha^{-1} yr^{-1}) but likely to be of ecological significance. While typologies could be distinguished based on the magnitude of modelled reductions in the quantities of P lost, the lack of a consistent effect that could be attributed to typology attributes within these groups makes it difficult to identify where decreases in P loss could be targeted in particular. This may be improved by further analysis considering the whole land area required to support milk production on each farm instead of using the effective farm area only. This is because some blocks (e.g. winter forage blocks) often make disproportionately large contributions to farm P losses. In addition, analysis using OVERSEER farm files that have measured instead of default soil Olsen P data for all blocks across the farm would reduce the uncertainty associated with using assumed values, as we have done here.

9.3 Details of assumptions used and changes made for mitigations

Mitigation 1: Tidy up existing farm management (Good Management Practice).

The following changes were made to ensure current best management practices for N, P and cropping losses are adhered to as detailed in Table 9.3.

Table 9.3. Assumptions used for applying mitigations within OVERSEER.

GMP	Assumptions/changes made
Stock excluded from streams	Based on Clean Stream Accord assessments
Optimum agronomic Olsen P	Olsen P changed to agronomic optimum; 30 for volcanic, recent, sedimentary and podzol soils; 45 for pumice and peat soils.
Low solubility P fertiliser sources used on farms in typologies with poorly drained soils or sloping contour	P fertiliser to RPR if rainfall > 800 mm or serpentine super if less[1]. pH assumed to be < 6.
P fertilization in high risk months avoided on farms with poorly drained soils or sloping contour	Late autumn/winter P fertiliser applications (May-July inclusive) were shifted to more appropriate months
Feed storage facilities are designed to minimise wastage, leachate, and soil damage, i.e. sealed or compacted surface	
Avoid or reduce N use over winter	Shift May applications to April; June, July applications to August up to 40 kg N ha^{-1} with any extra applied in April
Avoid excessive N fertiliser application rates to pasture.	Where applications exceeded 40 kg N ha^{-1} applic^{-1}, reduced to 40 kg N ha^{-1}, but kept total annual input same. Used 50 kg N ha^{-1} as a threshold for farms in the two irrigated typologies.
Avoid excessive N inputs to crops	Limit N inputs to crops to industry recommended levels.[1]
Strategic grazing of winter forage crops	

Manage runoff from tracks and races (divert or contain runoff, maintain track condition, improve drainage, fence races)
Manage runoff around gates and troughs
Manage stock crossings (put in/manage culverts, bridges)

Note[1]: FAR 2009 Best management practises for growing maize on Dairy farms; DairyNZ farmfacts 1-74, 1-76, 1-77, 1-62, 1-72 a, b; Specialty seeds NZ handbook.

Mitigation 2: Improve effluent management (an Improved Management Practice).

Management was improved by changing the effluent system from two pond + discharge to land application to pond with application rates of 12-24 mm or less. Change effluent applications to actively managed. Increase effluent area so that total K inputs (fertiliser + effluent + supplements) are less than 75 kg K ha^{-1}. Extend effluent area, or reduce N fertiliser inputs, so that total N inputs are less than 200 kg N ha^{-1}. Ensure sufficient pond storage and the use of low rate effluent application methods on farms in poorly draining typologies or typologies with sloping ground. Limit effluent application to low risk months (August to April) on farms in poorly drained and sloping typologies.

Where the N fertiliser rate was lowered, it was assumed that pasture production would be lowered by a calculated amount, with stocking rates adjusted accordingly assuming an intake of 4500 kg DM cow^{-1} year^{-1}. The reduction of pasture production with decreasing N fertiliser inputs was calculated using a sliding scale: N reductions from >350 kg N ha^{-1} year^{-1} to 350 kg N ha^{-1} year^{-1} were considered to have no effect due to an expected lack of N response at such high application rates (Shepherd et al. 2015; Monaghan et al. 2005). The expected N response from 350 kg to 250 kg N ha^{-1} year^{-1} was assumed to be 50% of that recommended by DairyNZ (farmfact 7-10; Monaghan et al. 2005). From 250 to 200 kg N ha^{-1} year^{-1} it was assumed that increased fertiliser N efficiency combined with effluent N would result in no loss of pasture production. When reducing stocking rates to offset reduced pasture production, milk solids production was reduced in proportion to the peak size of the milking herd, but only after per-cow production was increased by 10% to a maximum of 450 kg MS cow^{-1}.

Mitigation 3: Reduce N imported into farm; Stage 1 (an Improved Management Practice).

Supplement feeds imported onto the farm were changed to low N feeds as outlined in Table 9.4. Fertiliser N inputs to the milking platform were further reduced so that supplement + fertiliser N is less than the median figure for the group of typologies as indicated by the N threshold in Table 9.4. Reductions in pasture production caused by decreasing N were calculated as per the sliding scale used for mitigation 2. Where N application rates dropped below 200 kg N ha^{-1} year^{-1} it was assumed that production responses to the imported N would have been as recommended by DairyNZ (farmfact 7-10). As before, reduced pasture production was offset by a reduction in stocking rate, and a corresponding reduction in milk solids production in proportion to the peak size of the milking herd, but only after per-cow production was increased by 10% above that of the base farm, to a maximum of 450 kg MS cow^{-1}.

Table 9.4: Assumptions for low N feed and N inputs for mitigation 3.

Supplements	Assumption
North Island - shed fed supplement	Low N feed = Maize grain
North Island - paddock, feed lot supplement	Low N feed = Maize silage
Canterbury - shed fed supplement	Low N feed = Maize grain
Canterbury - paddock, feed lot supplement	Low N feed = Maize silage
Otago, Southland - shed fed supplement	Low N feed = Wheat/Barley grain
Otago, Southland - paddock, feed lot supplement	Low N feed = Cereal silage
Typology	**N threshold**
Low input farms	150 kg N ha^{-1} year^{-1}
Medium input farms	200 kg N ha^{-1} year^{-1}
High input farms	250 kg N ha^{-1} year^{-1}

Mitigation 4: Improved irrigation management (an Improved Management Practice).

Irrigation was changed to Linear or Centre-pivot with monitoring of soil moisture as shown in Table 9.5 for farms in the two irrigated typologies. Where farmers had already installed soil monitoring tapes or probes, the irrigation management was not changed. Further modification was done to the irrigation strategy to see if further improvement could be made using variable depth and variable application techniques

Table 9.5. OVERSEER irrigation settings.

OVERSEER settings	Assumptions/changes made
Irrigation system type	Linear and centre pivot
Irrigation management based on	Soil water budget
Strategy	Trigger point; fixed depth applied
Management systems definition	Default
Variable depth variable application irrigation strategy	Trigger point and depth applied to achieve target

Mitigation 5: Wetlands (an Advanced Practice)

Install an artificial wetland into farms in typologies that contain rolling contour or poorly-drained soils. In the absence of artificial drainage, the wetland was applied to the milking platform at the block level, with assumptions as per Table 9.6. Where pastoral blocks were artificially drained, wetlands capturing the drainage were added as part of each individual block while ensuring that 75-80% of the farm drained through a wetland.

Table 9.6. OVERSEER wetland settings.

OVERSEER settings	Assumptions/changes made
Effective wetland area	2% of catchment area which is 75% of milking platform area
Wetland condition	Artificial type 1: Flow path length to width ratio >5 (2 or more stage wetland, with even elongated channel or serpentine path created using internal bunds), well vegetated with good dispersion and even flow through the majority of wetland and minimal channelization or dead-zones
Wetland type	Wetland type A: Water always flows; Dominated by sedges and reeds, may contain flaxes willows etc.
Catchment area	75 to 80% of milking platform area.
Catchment convergence	Moderate for poorly drained typologies. High for rolling typologies
Aquitard area	Default.
Distribution of catchment area	Where a support block was included this was ticked with areas assigned to milking platform blocks only.

Mitigation 6: Reduce N imported into farm: Stage 2 (an Advanced Practice)

A further reduction of N fertiliser inputs to the milking platform so that supplement + fertiliser N is less than the 25th percentile threshold for group of typologies concerned (Table 9.7). Nitrogen fertiliser inputs were primarily targeted for this mitigation, firstly to ensure sufficient supplements are retained to apply mitigation and secondly to improve ease of modelling. Further reductions in pasture production caused by decreasing N were calculated as per the scale used for mitigations 2 and 3, with per cow production and stocking rate also adjusted accordingly.

Table 9.7: Threshold for N inputs for mitigation 6.

Typology	N threshold
Low input farms	100 kg N ha^{-1} $year^{-1}$
Medium input farms	140 kg N ha^{-1} $year^{-1}$
High input farms	180 kg N ha^{-1} $year^{-1}$

Mitigation 7: Off paddock managements (an Advanced Practice)

Improved wintering strategies were implemented by the addition of a covered wintering structure with grazing restricted to 12 hours day^{-1} from the beginning of March to the end of July. The structure is assumed to be used as described by settings entered into OVERSEER as shown in Table 9.8. Where cows were on pre-existing structures at other times of the year, those managements were continued. Supplements directed to a pre-existing structure other than the milking shed were transferred to the covered wintering structure. Imported supplement and crops harvested on farm were then directed to the wintering barn as required to ensure cows received 4 kg DM cow^{-1} day^{-1} from March to July. To avoid changing imported N inputs and keep pasture production the same, any shortfall was filled by using or making silage on the milking platform.

Table 9.8. OVERSEER wintering barn settings.

OVERSEER settings	Assumptions/changes made
Pad type	Covered wintering barn or animal shelter
Bunker lining material	No lining material
Bunker cleaning method	Scraping (no water) Scraped material stored in stack
Solids management	Spread on selected blocks (whole milking platform)
Storage method	Covered (from rain)
Time in storage	5 months
Feeding regime	Wintering pad + Grazing

9.4 Changes in farm management and production as a result of applied mitigations.

The application of mitigations, in particular mitigations bundles 2, 3 and 6 meant that some adjustment in stocking rate was necessary, which in turn resulted in a small drop in milk production. These changes were minimal, with stocking rate changing by 5% (range 3 - 8%), with the greatest change occurring for the poorly drained irrigated typology (Figure 9.1A). The increased per cow production did, however, offset these changes so that overall milk production (kg MS ha^{-1}) only dropped by 2% on average (range 1 - 4%; Figure 9.1B). The application of mitigation 2 improved effluent management, resulted in the average effluent area per farm increasing from 45 ha (24% of farm area) to 100 ha (52% of farm area).

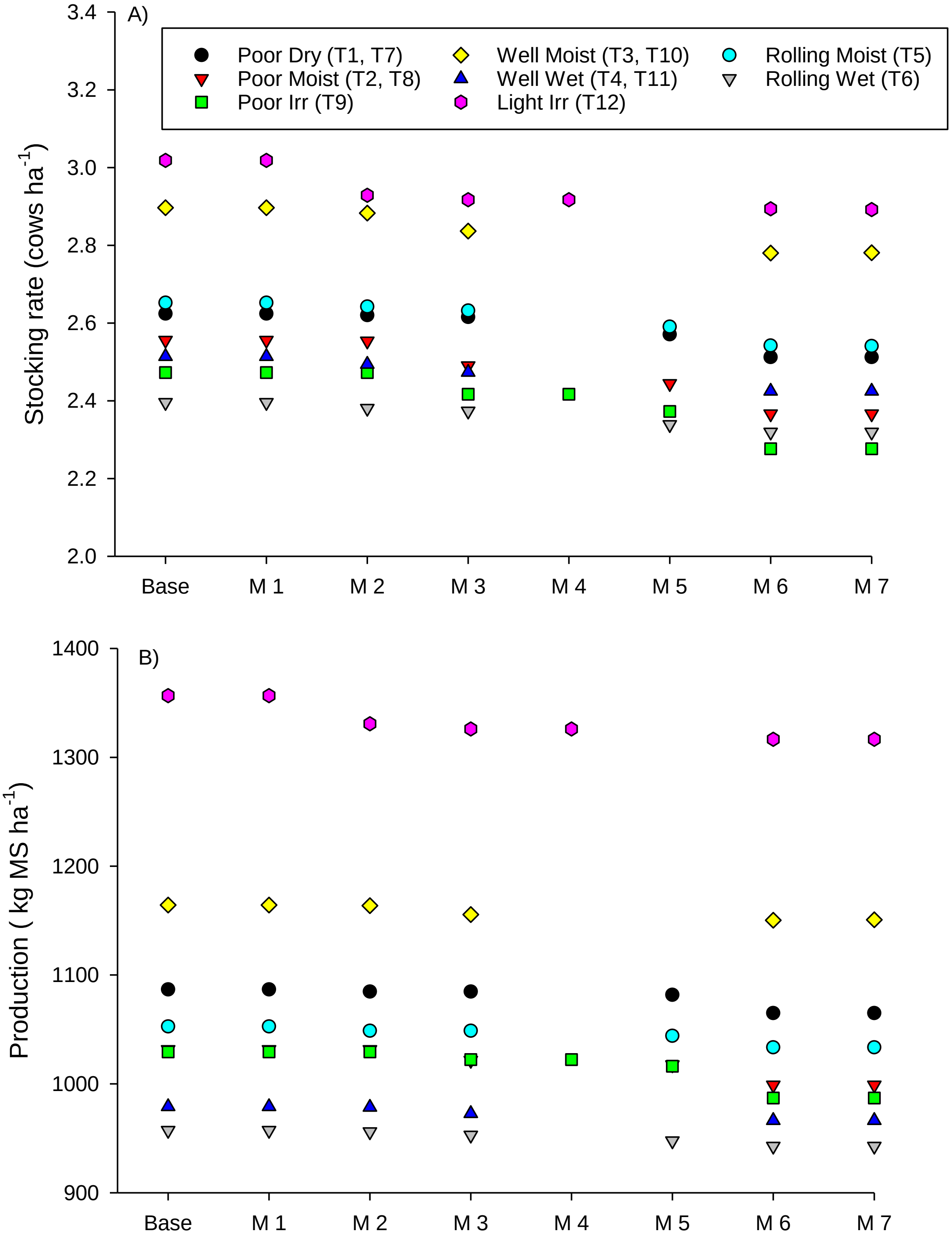

Figure 9.2 Reductions in A) stocking rate (cows ha^{-1}) and B) milk production (kg MS ha^{-1}) resulting from the progressive implementation of selected mitigation measures. Note that poor, well, light and rolling refer to drainage and contour status while dry, moist and Irr refer to wetness status of the typologies.

9.5 Potential modelled effects of individual mitigations on N and P losses

While the progressive application of mitigations on actual farms is discussed previously in this report, some idea of individual mitigation effects can be gleaned from a constructed average farm from each typology. This assessment of the effects of individual measures was undertaken as part of an associated programme of work funded by the Our Land and Water National Science Challenge (within the Sources and Flows objective); results are presented here in Tables 9.9 and 9.10 as a brief summary of these assessments. The effects of each mitigation represent the difference in N or P loss between a Base (un-mitigated) and mitigated farm.

Table 9.9. The likely effects of some individual mitigations on modelled N loss (kg N ha^{-1} yr^{-1}) from the milking platforms Typologies are categorised by drainage (light, poorly- or well-drained soils) and moisture (dry, moist, wet or irrigated) status; Roll refers to farm typologies on rolling topography.

Typology[#]		Base farm	M 1	M 2				M 3
			No Winter N	Land Applic.	Optimum area	Low rate	Reduced N	N inputs 1
T1 + T7	Poor, Dry	26	1	13	0	0	3	3
T2 + T8	Poor, Moist	33	2	8	3	5	0	1
T9	Poor, Irr	47	0	6	1	2	0	5
T3 + T10	Well, Moist	37	1	11	0		0	3
T 4 + T11	Well, Wet	57	2	8	5		1	4
T12	Light, Irr	62	2	14	0		0	7
T5	Roll, Moist	36	0	7	1	2	0	2
T6	Roll Wet	47	2	10	0	0	0	4

		Base farm	M 4		M 6	M 7		
			No border dyke	Improved mgmt	N inputs 2	Wintering off pasture	Wintering off crop	Restricted grazing aut/win
T1 + T7	Poor, Dry	26			5	11	6	12
T2 + T8	Poor, Moist	33			14	6	24	9
T9	Poor, Irr	47	29	63	30		28	10
T3 + T10	Well, Moist	37			5	9	7	13
T 4 + T11	Well, Wet	57			6	9		21
T12	Light, Irr	62	23	105	19		7	30
T5	Roll, Moist	36			7	6		13
T6	Roll, Wet	47			4	6		14

[#] Poor, Well and Light terms denote poorly-drained, well-drained and Light soils, respectively; Roll refers to farms on rolling topography; and Irr refers to irrigated farms.

Table 9.10. The likely effects of some individual mitigations on modelled P loss risk (kg P ha^{-1} yr^{-1}) from the milking platforms. Typologies are categorised by drainage (light, poorly- or well-drained soils) and moisture (dry, moist, wet or irrigated) status; Roll refers to farm typologies on rolling topography.

Typology[#]		Base farm	M 1			M 2	
			No Winter P	Optimum Olsen P	Low Sol P	Land Applic.	Low rate
T1 + T7	Poor, Dry	1.1	0.0	0.1	0.1	1.4	0.0
0T2 + T8	Poor, Moist	1.3	0.1	0.2	0.2	0.9	0.0
T9	Poor, Irr	0.9	0.0	0.0	0.0	0.9	0.0
T3 + T10	Well, Moist	1.0	0.1	0.3		1.2	
T 4 + T11	Well, Wet	0.7	0.0	0.1		1.0	
T12	Light, Irr	0.6	0.0	0.0		1.2	
T5	Roll, Moist	1.8	0.0	0.1	0.6	1.2	0.1
T6	Roll Wet	1.7	0.2	0.2	0.3	1.4	0.0

		Base farm	M 4	
			No border	Improved mgmt
T1 + T7	Poor, Dry	1.1		
T2 + T8	Poor, Moist	1.3		
T9	Poor, Irr	0.9	5.8	0.9
T3 + T10	Well, Moist	1.0		
T 4 + T11	Well, Wet	0.7		
T12	Light, Irr	0.6	4.5	0.3
T5	Roll, Moist	1.8		
T6	Roll, Wet	1.7		

[#] Poor, Well and Light terms denote poorly-drained, well-drained and Light soils, respectively; Roll refers to farms on rolling topography; and Irr refers to irrigated farms.

9.6 Possible benchmark ranges for N, P and GHGs based upon the farm units represented by the OVERSEER farm file areas provided from Dairybase.

Table 9.11. Suggested benchmark ranges for N, P (kg $ha^{-1}yr^{-1}$) and GHGs ($CO_{2eq.}$ $ha^{-1}yr^{-1}$) from the OVERSEER files as defined by median and 25th and 75th percentile values for each of the identified key typology groupings.

Issue	Primary typology attribute	Secondary typology attribute	Median value	25th, 75th %iles.
N	Poorly-drained soils	All	31	23, 39
	Light soils	Irrigated	81	47, 110
		Other	44	33, 57
	Well-drained soils	Dry	30	25, 37
		Moist	38	30, 53
		Wet	50	41, 62
		Irrigated	77	57, 114
GHG	Irrigated farms	All	11670	9573, 13617
	Non-irrigated: Winter warm	Flat	10842	9497, 12059
		Rolling	9626	7845, 11134
	Non-irrigated: Winter cool	All	8976	7553, 10152
P	Low ASC	Dry	0.57	0.43, 0.68
		Moist	1.40	1.05, 1.83
		Wet	2.54	1.98, 2.67
		Irrigated	0.93	0.92, 1.60
	All soils	Flat land	1.05	0.80, 1.47
		Rolling	1.42	1.21, 1.89

9.7 Relationship between plant available water (PAW) and N leaching losses.

The relationship between PAW and estimated N leaching for farms is shown in (Figure 9.3). A negative relationship between these variables is broadly evident, although there is much scatter evident. No relationships between these variables were evident when plotted for individual typologies (Figures 9.4 – 9.6). This indicates that PAW is only one of a number of variables influencing estimates of N leaching; other physical and management factors appear to be more important when examining within typology units.

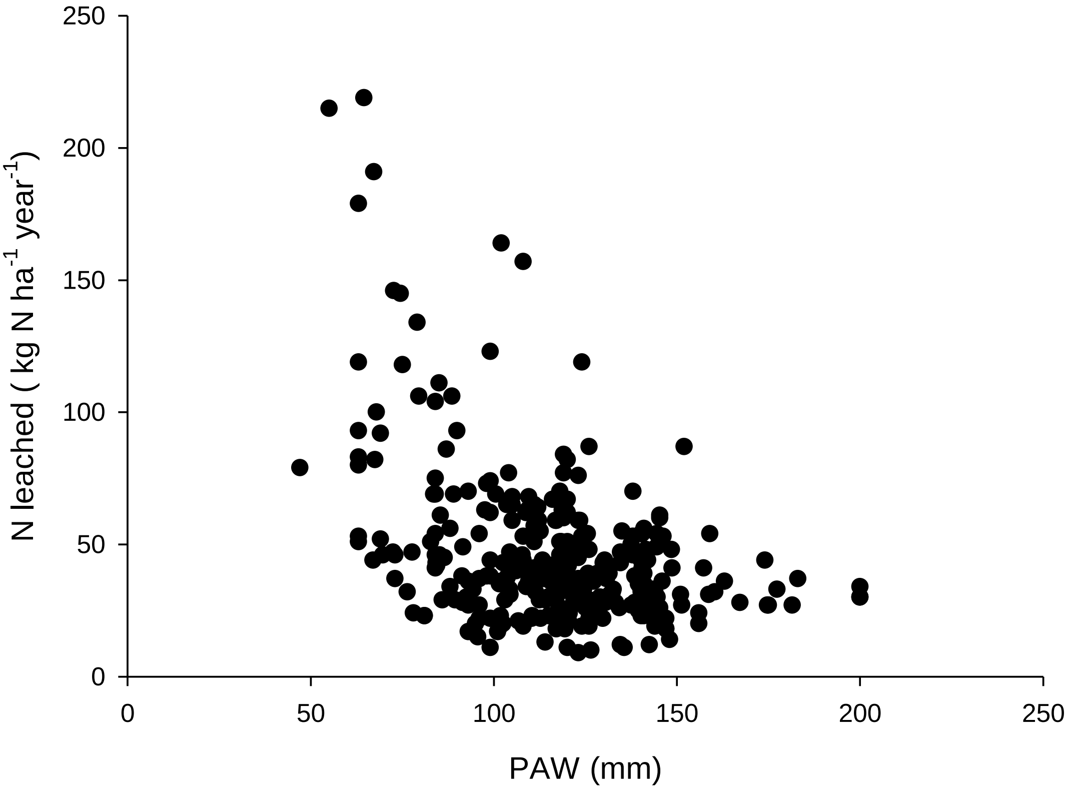

Figure 9.3. Relationship between plant available water (PAW) and N leaching losses from the OVERSEER files (all farms).

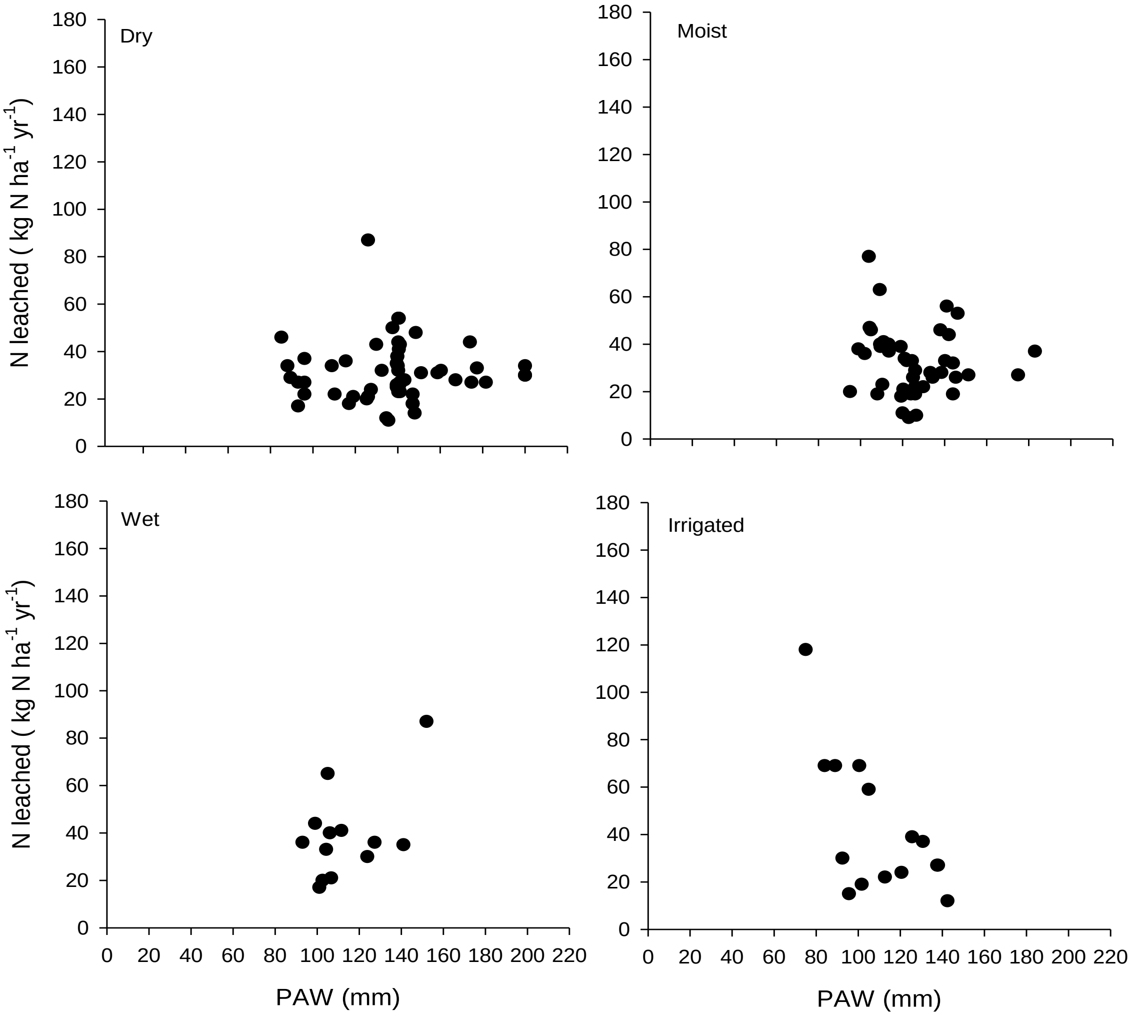

Figure 9.4. Relationship between plant available water (PAW) and N leaching losses from the OVERSEER files for the typologies with poorly drained soils.

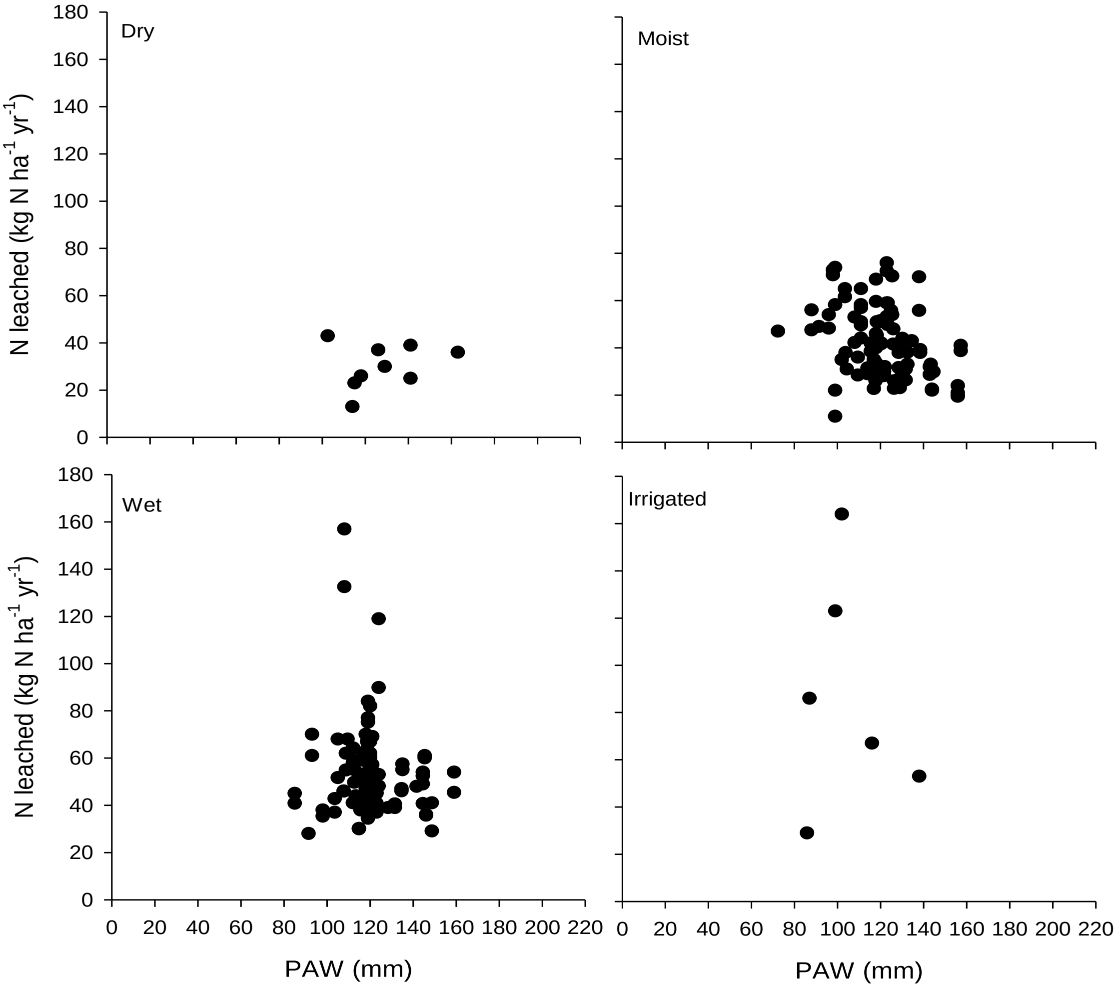

Figure 9.5. Relationship between plant available water (PAW) and N leaching losses from the OVERSEER files for the typologies with well drained soils.

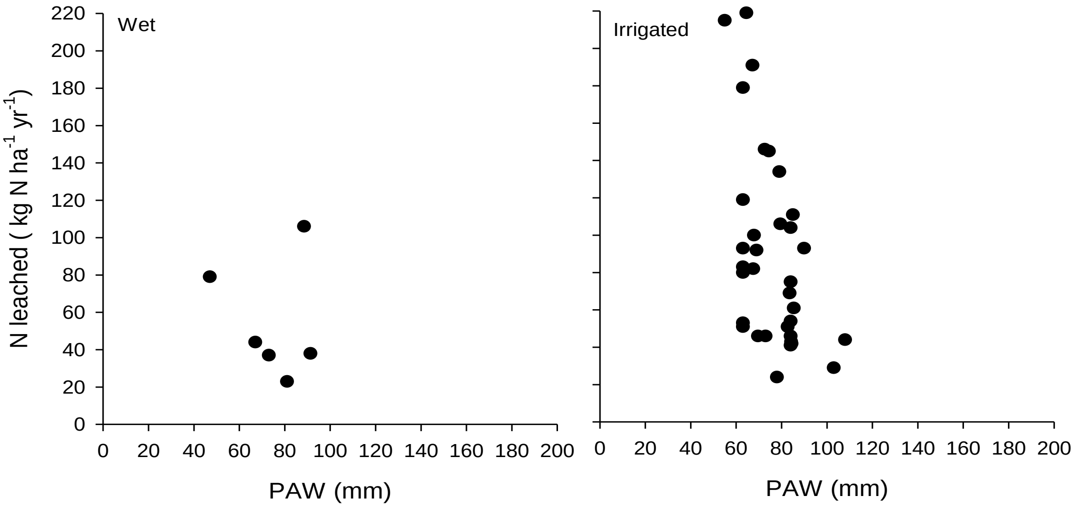

Figure 9.6. Relationship between plant available water (PAW) and N leaching losses from the OVERSEER files for the typologies with light soils.

9.8 Assessments of reductions in sediment loss risk

Given our limited ability to model sediment losses at a farm scale, the assessments undertaken here are provided as qualitative estimates of the likely responses to some of the mitigation measures considered in our overall analysis of mitigation effectiveness. The approach for doing so is described below.

Sediment sources and key farm typologies

Four key sources of sediment were identified and used to construct an inventory of sediment loss for relevant dairy farm typologies:

1. stream bank (and bed) erosion
2. discharges from mole-pipe drains
3. surface runoff from tracks and lanes.
4. surface erosion

The potential contribution from livestock fording streams was ignored for the purposes of the assessments reported here.

The key typology attributes that were deemed to most influence sediment loss were those that influenced surficial erosion: slope, wetness and soil drainage. The key typology groupings that were assessed for sediment loss risk were therefore categorised into the landscape categories listed below and assessed for Dry, Moist and Wet environments:

1. Flat land:
    - Well-drained soils
    - Poorly-drained soils
2. Rolling land:
    - Well-drained soils
    - Poorly-drained soils

Light soils and irrigated farm typology groups were excluded from our analysis due to their assumed low level of sediment loss risk.

An inventory of sediment loss from each source was constructed for each typology grouping following the approach documented below.

Sediment inventory calculations and assumptions

1. Stream bank and bed erosion

It was assumed that a fixed amount of sediment could be lost from farms and catchments due to erosion caused by allowing stock access to streams i.e. this source was independent of farm typology category. Here we assumed that this source represented 81 kg sediment per hectare per annum. This figure was based on measured decreases in sediment yields in 3 intensively-farmed dairy catchments where specific yields of sediment were monitored over an extended monitoring period (up to 10 years); much of this decrease was attributed to the widespread implementation of measures that prevented stock accessing streams and stream banks (Wilcock et al. 2007, 2013). The source value assumed here is thus likely to be a very conservative one – it is likely that the full response to stream fencing will occur over a monitoring period greater than 10 years, and not all of the sediment lost to the stream will necessarily discharge from the catchment outlet.

2. Discharges from mole-pipe drains

Mole-pipe drains are recognised as small but potentially significant sources of sediment (and P and faecal microorganisms; Monaghan et al. 2016). A source load of 48 kg sediment per hectare per year was therefore added to the inventory for typology categories where mole pipe drains were likely to occur (poorly-drained soils on flat land).

3. Laneway runoff

Surface runoff from farm tracks and lanes is also recognised as a source of sediment, P and faecal micro-organisms discharges to streams (Monaghan & Smith, 2012). Although this source load is likely to be minor in most situations, for completeness a load representing the equivalent of 1 kg per hectare per year was added to the inventory, for all farm typology categories.

4. Surface erosion

The Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997; Dymond 2010) was used to calculate potential sediment generation on the landscapes represented by the key typology categories described above. Whilst this tool was mainly developed for cropping systems in parts of the US and has not been designed to describe the consequences of intensive grazing on sediment discharges to water, it does provide a common framework that considers most of the key factors that drive surface soil erosion from farmed landscapes of less than 15^o slope: rainfall energy, soil erodibility, slope, slope length, soil cover and an assortment of management practices that influence soil strength and susceptibility to erosion. An important advantage of the RUSLE is its potential utility for estimating the mitigation effect of strategic grazing of winter forage crops located on contrasting soil and slope landscape attributes. The approach and assumptions used to calculate sediment loss via the RUSLE equation are described below. Soil loss estimates were calculated as the area-weighted average loss from pasture and crop areas, which were assumed to occupy 90 and 10% of farm area, respectively, for farm typologies where winter forage cropping was practised.

Rainfall and runoff factor (*R*). Calculated from Klik et al (2015), assuming typical annual rainfall inputs for Dry, Moist and Wet typology categories of 900, 1200 and 1800 mm, respectively, and assuming a rainfall erosivity typical of eastern and southern parts of the South Island of NZ.

Soil erodibility (*K*). Values derived from Renard et al. (1997), based on soil attributes for the most common soil type settings entered into the Dairybase OVERSEER files.

Slope (*S*) and slope length (*L*). Derived from Renard et al. (1997) for a standard slope length of 50 m and slopes of either 2º (Flat land) or 8º (Rolling land).

Cover and management (*C*). The value for grazed winter forage crops was derived as the factor that delivered the closest agreement between measured and calculated (RUSLE) losses reported for the Control treatment of the Telford winter grazing study (Monaghan et al. 2017). Values for well-drained and poorly-drained pastoral soils were set to 40% and 60% of that assumed for grazed winter forage crop areas.

Support Practice (*P*). Set to a value of 1, unless the strategic grazing and off-paddock mitigation measures were assumed to have been implemented (discussed further below).

Mitigation measures and assumptions

Relevant mitigation measures for controlling sediment losses from some of the above sources are (i) stock exclusion from streams, (ii) strategic grazing of crops, (iii) preventing runoff from laneways and around gateways and troughs (M1 mitigation bundle), (iv) wetlands (M5) and (v) off-paddock managements (M7). The individual effectiveness of each of these measures was assessed in the following way:

(i) Stock exclusion from streams was assumed to reduce sediment discharges from farms by 81 kg $ha^{-1}yr^{-1}$, as described above.

(ii) Strategic grazing of winter forage crops was assumed to reduce the Support Practice factor from a value of 1.0 to 0.2, based upon the relative reduction reported by Monaghan et al. (2017).

(iii) Eliminating runoff from laneways and hard surface areas was assumed to reduce sediment discharges from farms by the equivalent of 1 kg $ha^{-1}yr^{-1}$, as described above.

(iv) The installation of wetlands was assumed to capture 20% of the sediment discharged from poorly drained farm typologies, and from well-drained farms on rolling topography where wetland interception of farm runoff was assumed to be a plausible scenario (Hughes et al. 2013).

(v) Off-paddock management was assumed to have 2 effects:

   a. All wintering was assumed to occur off-paddock. Winter forage crop areas were therefore removed from the inventory as a source of sediment loss.
   b. The availability of off-paddock infrastructure was assumed to allow for on-off grazing during wet conditions. This scenario was assumed to protect pastures and soils on farms with poorly-drained soil attributes to a level equivalent to that for farms on well-drained soil types; accordingly, the Cover and Management factor (*C*) for pastoral areas of farms on poorly-drained soils was reduced to the value used for farms on well-drained soils.

Sediment loss risk inventory

The inventory of sediment sources is documented in Table 9.12. An apparent anomaly of note in this table is the unexpected decrease in losses via surface erosion that were estimated as wetness increased within some typology groupings. On further examination this response was found to be attributable to changes in the soil erodibility factor (*K*) that was assigned to some soil types: because of their relatively high soil organic matter contents, many of the soil types assumed for Wet typology attributes were found to have relatively low *K* values, in contrast to those determined for the more erodible (mostly Pallic) soils in Dry typology categories.

Sediment loss risk mitigation

Assessments of mitigation effectiveness for each of the measures detailed above are documented in Table 9.13. Summary results are also shown and discussed in section 5.3.

Table 9.12. Inventory of potential sediment sources (kg sediment ha^{-1}yr^{-1}, weighted for pastoral and crop areas) for key typology groupings.

Topography	Drainage	Wetness	Stream bank erosion	Mole-pipe drains	Laneway runoff	Surface erosion	Total potential source load
Flat	Poor	Dry	81	48	1	151	281
		Moist	81	48	1	86	216
		Wet	81	48	1	116	246
	Well	Dry	81	0	1	35	117
		Moist	81	0	1	82	164
		Wet	81	0	1	26	108
Rolling	Poor	Dry	81	0	1	562[a]	644
		Moist	81	0	1	320	402
		Wet	81	0	1	564	646
	Well	Dry	81	0	1	183	265
		Moist	81	0	1	137	219
		Wet	81	0	1	134	216

[a]representing an estimated area-weighted loss of 1080 and 500 kg sediment ha^{-1}yr^{-1} from winter crop and pastoral areas, respectively. For comparison, the measured mean annual sediment loss (2-year crop grazing sequence) from the winter forage crop site at Telford, south Otago, was 930 kg sediment ha^{-1}yr^{-1}.

Table 9.13. Assessments of sediment mitigation effectiveness (% reduction) for key typology groupings. Stock exclusion scenario compares the change (reduction) in estimated sediment loss risk between a farm without or with full stock exclusion from stream margins; remaining mitigation scenarios estimate reductions from a base farm that is assumed to have full stock exclusion from streams.

Topography	Drainage	Wetness	Stock exclusion	Strategic grazing of winter crops	Eliminating laneway runoff	Wetland interception	Off-paddock managements
Flat	Poor	Dry	35%	10%	1%	20%	25%
		Moist	48%	7%	1%	20%	16%
		Wet	41%	9%	1%	20%	21%
	Well	Dry	70%	20%	3%	0%	17%
		Moist	50%	20%	1%	0%	17%
		Wet	76%	20%	4%	0%	17%
Rolling	Poor	Dry	13%	15%	<1%	20%	37%
		Moist	20%	15%	<1%	20%	37%
		Wet	13%	15%	<1%	20%	37%
	Well	Dry	31%	20%	1%	20%	17%
		Moist	37%	20%	1%	20%	17%
		Wet	38%	20%	1%	20%	17%