Ministry for the Environment
Environment
Manatū Mō Te Taiao

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19-D-02726

s 9(2)(a)

Federated Farmers of New Zealand
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Dear s 9(2)(a)

Thank you for your email of 13 December 2019 requesting the following under the Official Information Act 1982 (the Act):

> *Recommendations and interim soils data to support the development of a national freshwater reporting model. Landcare Research Contract Report LC2380.*

The Ministry for the Environment has identified one document, the report you have requested, as being in scope of your request. That report is being provided to you in full, and is attached here.

The report was an interim step of a wider work programme. Details of the completed freshwater quality model used for environmental reporting are available here: https://www.mfe.govt.nz/publications/fresh-water/water-quality-new-zealand-rivers-modelled-water-quality-state.

You have the right to seek an investigation and review by the Office of the Ombudsman of my response to this request, in accordance with section 28(3) of the Act. The relevant details can be found on their website at: www.ombudsman.parliament.nz.

Please note that due to the public interest in our work the Ministry for the Environment publishes responses to requests for official information on our OIA responses page shortly after the response has been sent. If you have any queries about this, please feel free to contact our Executive Relations team: ministerials@mfe.govt.nz.

Yours sincerely

M.Workman

Martin Workman
Director, Water Directorate

LANDCARE RESEARCH
MANAAKI WHENUA

Recommendations and interim soils data to support the development of a national freshwater reporting model

Recommendations and interim soils data to support the development of a national freshwater reporting model

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Landcare Research

Prepared for:

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30 June 2015

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Landcare Research Contract Report:	LC2380

Disclaimer

This report has been prepared by Landcare Research for the Ministry for the Environment. If used by other parties, no warranty or representation is given as to its accuracy and no liability is accepted for loss or damage arising directly or indirectly from reliance on the information in it.

Subject to the terms and conditions of the Statement of Work contract, all S-map data and S-map related information supplied or created for this report must be kept confidential, and cannot be disclosed to any third party except:

- *a) With Landcare Research's prior written consent; or*
- *b) To the extent that the data or information is already in the public domain prior to this report; or*
- *c) As otherwise required by law.*

Contents

Summary

Project and Client

The Ministry for the Environment (MfE) has contracted Landcare Research to undertake a short but intensive project involving the provision of soils data, expertise, and advice to ensure S-map soils information is factored into the design of a freshwater model currently being developed by MfE.

Objectives

- Develop and supply an interim national soil layer (S-map based) with attributes relevant to nitrate leaching.
- Develop and supply a national rating of soil nitrate-leaching potential.
- Provide recommendations and options for integrating soil information into MfE's freshwater model.

Methods

- S-Map has been hybridised with the Fundamental Soils Layer (FSL) to a Statistics NZ geographical boundary using GIS techniques. Accuracy of the FSLs is determined by comparison with S-Map, and differing levels of confidence are assigned to each soil.
- The soil nitrate-leaching vulnerability index of Webb et al. (2010) is used to provide a rating of nitrate leaching potential for NZ. Index performance is compared against Overseer® N-leaching estimates for 1770 soils. Index accuracy for the FSL is determined by comparison with S-map. A literature review was undertaken to identify alternative methods and models for rating nitrate leaching potential.
- Structure of the freshwater model is reviewed to identify options for integrating soil information. Emphasis is directed at the Agricultural Intensity Model (AgIM).

Results and conclusions

We have generated an interim hybrid national soil layer that combines the latest S-map with the FSL database. S-map represents 28% of the layer (7.5 M ha).

- The reliability of the FSLs is generally poor relative to S-map. When the two are compared at the most detailed level of the NZ Soil Classification, the FSL has a classification accuracy of 0.17 (kappa = 0.13) and a map accuracy of 0.32 (kappa = 0.30), which equates to only slight and fair levels of agreement with S-map.
- Confidence for the entire hybrid database is rated as 6% High, 12% Medium, 11% Low, and 70% Very Low (mostly for FSL data).
- FSL-based options to improve the accuracy of the hybrid layer will likely involve substantial cost, but the results will still be of lower quality relative to S-map. More

effective options include integrating remaining legacy soil maps into S-map (~1 M ha) and supporting the acceleration of the S-map programme.

Nitrate leaching potential has been examined using the soil nitrate-leaching vulnerability index of Webb et al. (2010). When compared against Overseer® modelled N-leaching it achieves a reasonably strong relationship except at the Very Low vulnerability class:

- The vulnerability of NZ soils to nitrate leaching loss is rated as Very Low (5% of NZ soils), Low (25%), Moderate (19%), High (23%), and Very High (18%).
- The accuracy of FSL vulnerability ratings is generally poor relative to S-map. A classification accuracy of 0.32 (kappa = 0.12) indicates only slight agreement, and a map accuracy of 0.42 (kappa = 0.25) indicates fair agreement. Confidence for the FSL N-leaching vulnerability component of the hybrid layer is Low to Very Low.

Landcare Research is satisfied with the performance of the N-leaching vulnerability index, and will continue to update it for S-map purposes. However, we have considered several options that could provide an improved or alternative system of representing N-leaching potential across NZ:

- Improving the vulnerability index through the integration of bypass flow, improved estimates of denitrification, and deep drainage losses. Deep drainage and denitrification could be better accounted for using spatial daily water balances.
- Implement Overseer® or APSIM across all NZ soils using 'reference farm systems'. Relative N-leaching from soils under the same farm system can then be classified into a classification of N-leaching potential.
- As above, but use the APSIM model to generate N-leaching estimates for 'soil-climate-reference farm system' combinations across NZ. Validity of this option is vastly improved by recent automatic translation of S-map soil properties into APSIM equivalents.

A national layer of nitrate leaching potential does not immediately translate into a 'ready to use' option for the MfE freshwater model. For this, the most suitable overall approach would involve the stratification of the $\mathrm{Frac}_{\mathrm{LEACH}}$ component of the AgIM model (currently uses a single $\mathrm{Frac}_{\mathrm{LEACH}}$ value for all of NZ). We have identified three options:

1. Adaptation of the Canadian system of stratifying $\mathrm{Frac}_{\mathrm{LEACH}}$ using NZ-specific research and a national soil water balance.
2. Improvement of the 'representative Overseer® farms' method, originally used to develop NZ's current single $\mathrm{Frac}_{\mathrm{LEACH}}$ value. Improvements include a larger number of representative farms, and more rigorous determination of farm system design and soil-climate clusters (using the 'nitrate leaching potential' layer from this project).
3. Development of the 'reference farm system' approach, which uses a defined set of conditions (the reference) to generate a set of reference values (e.g. reference N-leaching).

Recommendations

- That MfE use the national hybrid soil map in the freshwater model, but with recognition that it is an interim dataset and the FSL component (72%) has low accuracy and Low to Very Low confidence.
- To commission regular updates to the hybrid layer to improve accuracy as S-map coverage grows (e.g. updates that correspond with freshwater domain periods).
- Invest in the development of a stratified $Frac_{LEACH}$ for NZ. All three options described in this report are valid, but differ in terms of risk and rigour:

    1. An adapted Canadian method is recommended as a simple and safe option. The general method is already accepted by the IPCC (i.e. achieves their standard). However, the method does not capture differences between land uses.

    2. The 'representative Overseer® farms' method is recommended as the most robust option for accommodating both land use and soil-climate influences on $Frac_{LEACH}$.

    3. The 'reference farm system' is recommended as a suitable option with high potential (including for purposes other than stratifying $Frac_{LEACH}$), but is the least developed option (i.e. this option has the greatest uncertainty).

- Any development of a stratified NZ $Frac_{LEACH}$ will need to achieve Tier 1 statistics standards. For this we recommend the establishment of a multi-disciplinary development team including MPI, and a published journal paper specified as a key output.
- There will be a scale-mismatch between APS data (farm units) and stratified $Frac_{LEACH}$ values (soil-climate units). We have made suggestions on how this can be managed, but further consideration is required.
- Rebuild the AgIM model in a spatial modelling framework. With the existing design there will be considerable (inefficient) crossover between GIS and the AgIM spreadsheet, and a spatial AgIM would resolve scale-mismatch issues and allow for rapid testing of any GHG inventory or AgIM downscaling proposals.

1 Introduction

Environmental reporting in New Zealand is currently being overhauled. Government has proposed a new Environmental Reporting Bill that aims to fundamentally improve the credibility, certainty and independence of national environmental reporting (MfE 2011). Currently the Bill is before Parliament, and is anticipated to pass into law before the end of 2015 (Statistics NZ 2015). Considerable work is already underway 'in the spirit of the Bill' (MfE & Statistics NZ 2015).

The Ministry for the Environment (MfE), together with Statistics NZ (Statistics NZ), will share a co-production responsibility to prepare reports on five domains (air, atmosphere and climate, land, freshwater, and marine) using a new generation environmental reporting framework. Indicators currently under development must align to a rigorous quality standard (Tier 1 Statistics), and are subject to final approval by the Government Statistician. Domain reports are currently being produced, and the first synthesis report is due in October 2015 (MfE & Statistics NZ 2015).

For the freshwater domain, MfE have embarked on the development of a new modelling framework for reporting on pressures regarding contaminant discharges to freshwater. *Nitrate leaching* is proposed as the first contaminant pressure indicator, but may be followed in time by indicators of phosphorus loss, sediment, and E. coli.

Nitrate leaching is strongly influenced by the properties and characteristics of individual soils. Field and lysimeter-based studies discussed in this report have demonstrated 1.4- to 3.3-fold increases in N-leaching attributed to soil type alone, while Overseer® modelling of all S-map siblings suggests that a change in soil has the potential to produce up to 6–8-fold differences in N-leaching estimates.

Landcare Research is the lead Crown Research Institute (CRI) regarding soil characterisation, processes, and services (LCR 2014), and has been contracted by MfE to provide soils data and advice for the development of the freshwater model. This report outlines the development of an interim national soils layer based on S-map, a national classification of soil nitrate-leaching potential, and advice on how and where soil information can be integrated into the freshwater model.

2 Background

2.1 Overview of MfE's freshwater model

MfE's freshwater model is being developed as part of a three stage work programme. Here we provide an overview of all stages (Fig. 1). More specific detail regarding Stage 1 is provided by Ausseil et al. (2015), while Section 5.4 of this report discusses parts of Stage 2 in greater detail. We have limited information regarding Stage 3, which is under development by NIWA and MfE.

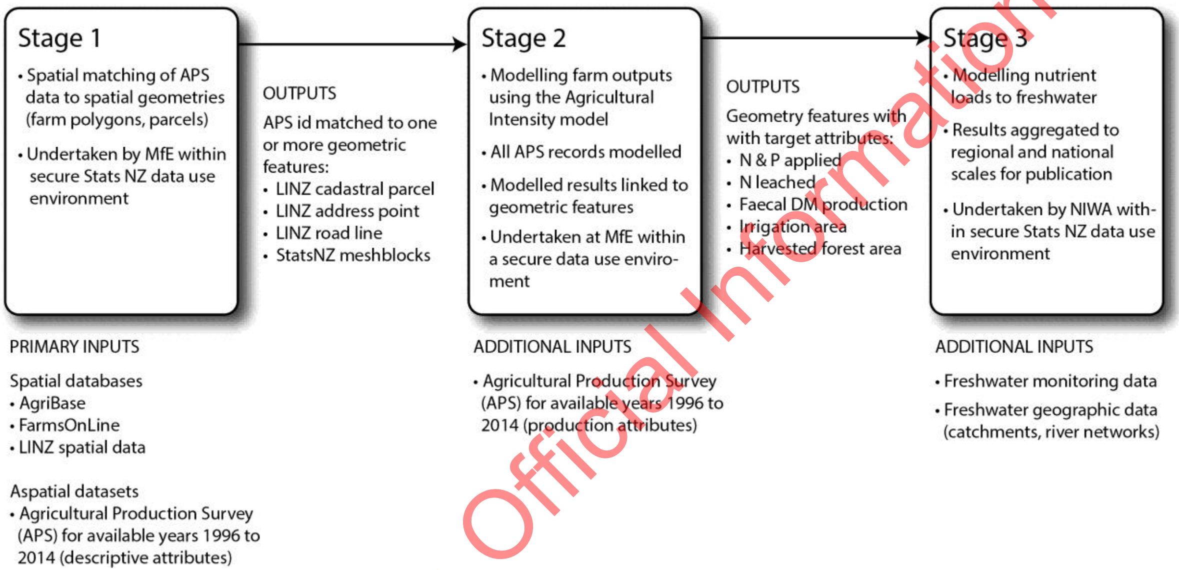

Figure 1 Provisional overview of MfE's freshwater model.

2.1.1 Stage 1: Data matching

Stage 1 is a data matching project, which aims to link a time series of Agriculture Production Survey (APS) data to LINZ cadastral parcels, address points, road centre lines, or Statistics NZ meshblocks (Statistics NZ 2015). Key components include (after Ausseil et al. 2015):

- APS time series data (1996–2014). The APS collectively describes the *agricultural production census* (undertaken once every five years, with a target population of approximately 80 000 farm businesses drawn from Statistics NZ Business Frame), and the *agricultural production survey* which is undertaken annually between censuses (using a stratified sample of approximately 30 000 farm businesses). Both are compulsory, and both generally achieve a high standard of statistical rigour. The current APS programme has been running since 2004. Before this the APS record used a variety of methods, and no data were collected for 1997 and 1998. The APS contains a rich set of data on individual farms (location, ownership, land use, production, and activities such as irrigation, fertiliser use, effluent application, and nutrient budgeting), and its use is protected under the Statistics Act 1975.

- Spatial databases used in the data matching project include AsureQuality's AgriBase^{TM}, which contains records for approximately 135 000 farms (access by commercial license); FarmsOnLine, which claims full representation of all rural properties (limited access authorised by MPI's Director-General); and cadastral data from LINZ (creative commons licensing). Collectively, these databases contain the names, addresses, and spatial boundaries for every farm and rural land parcel in NZ.
- Record matching. Both commercial and open-source software are used to mine matching details between the APS and the spatial database collection. If matches are strong, the corresponding APS id is assigned to the farm and eventually the corresponding LINZ land parcel(s). Weak or unmatched records are assigned to a point location, road centreline, or meshblock.
- Strict data access and use restrictions. In particular the APS is protected under the Statistics Act 1975. Only those authorised under the Act are allowed to see the data, and the data itself can only be used for approved statistical purposes, and final release remains at the discretion of the Government Statistician. However, Statistics NZ have already concluded that project has clear value and benefits, and that privacy, security and confidentiality risks are being appropriately mitigated (Statistics NZ 2015).

2.1.2 Stage 2: Modelling farm outputs

In tandem with Stage 1, key farm production data have been extracted from the APS to model each farm through a modified version of NZ's Agricultural Greenhouse Inventory (AgGHG) calculator.

- The AgGHG calculator is a spreadsheet model that is used to calculate NZ's livestock GHG emissions as part of the national GHG Inventory (MfE 2015). It adheres to IPCC standards that are similar to those for Tier 1 statistics (transparent, accurate, complete, consistent between years, comparable between countries), which makes it suitable for the freshwater model project. Methods and mechanics are particularly well documented (Clark et al. 2003; Clark 2011; Pickering 2013).
- The AgGHG uses national and regional livestock and production statistics, mostly from the APS, but also additional statistical summaries from MPI and industry sectors. Process involves the calculation of total dry matter intake (DMI), which is used to estimate enteric methane (emissions from rumination) and excreta production, which in turn is used to estimate both excreta methane losses and the proportion of nitrogen returned to the environment. The results are multiplied by emission factors according to different emission pathways. The NZ emission factor for N-leaching ($FRAC_{LEACH}$) is 0.07, meaning that a uniform 7% of excreta-N deposited during grazing (as dung and urine N) is assumed to be lost via leaching.
- The AgGHG calculator has been modified by AgResearch to accept multiple records, to facilitate the modelling of many farms simultaneously. The modified version is differentiated as the Agricultural Intensity Model (AgIM).

- Outputs from Stage 2 include N-leaching and faecal dry-matter production from AgIM, along with APS data for fertiliser use, irrigation area, and area of harvested forest (used to contribute towards the development of other indicators).
- Stage 2 is undertaken within a secure data lab that has been created at MfE (and approved by Statistics NZ) especially for the freshwater modelling project.
- A dataset will be retained by Statistics NZ to allow, if required, Statistics NZ or approved MfE staff, to quality assure the source and input data of Stage 3 outputs.

2.1.3 Stage 3: Modelling nutrient loads to freshwater

Stage 3 is undertaken by researchers from NIWA. Their role is to use Stage 2 outputs as a basis for modelling nutrient loads to freshwater.

- NIWA will map the output from Stage 2 onto known information for river, lake, and groundwater quality. Water quality changes overtime are measured primarily in terms of nitrogen and phosphorus content, water clarity, and E. coli concentration, and allow for river flow by measuring the rate of flow from mountain to sea, and water taken for irrigation.
- Results are aggregated into geographic regions, or areas that ensure no individual farm can be identified in the final output. Publication will be at regional and national scales. Final approval is required to ensure results meet Statistics NZ's strict confidentiality provisions, quality assurance levels, and data integrity standards. Publication is at the sole discretion of Statistics NZ and the information is targeted for release within the first Freshwater Domain Report due in 2016.
- Stage 3 modelling is undertaken within a secure data environment located at Statistics NZ, Christchurch.

Considerable care and use-restrictions are implemented throughout the three stages, with each stage successively discarding details that can be used to identify individual farm properties.

2.2 Soils and nitrate leaching

Three basic conditions must be satisfied for nitrate leaching to occur. First, nitrate must be present in the soil, which is initially a function of inputs (animals, plants, fertilisers, and atmospheric deposition) but is also largely influenced by soil processes and transformations associated with the nitrogen cycle (Fig. 2). Second, the soil must be permeable to facilitate water movement, and third, water movement leading to deep drainage must actually be occurring. If the input dimension is put to one side, all three conditions are governed to differing extents by soil characteristics, processes, and properties, all of which can vary markedly between soils.

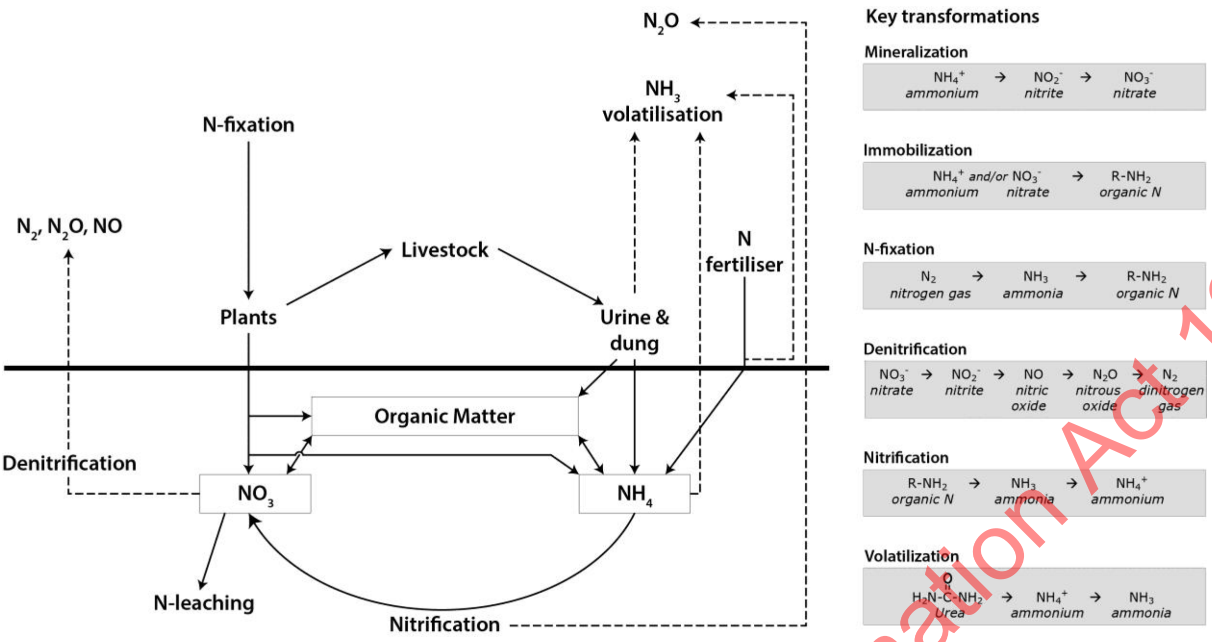

Figure 2 Basic nitrogen cycle with key transformations (adapted from Giltrap et al. 2014).

2.2.1 Presence of nitrate and nitrogen transformations

Nitrate (NO_3) is the primary form of leached nitrogen (ammonium NH_4 also leaches but at much reduced levels), the availability of which is influenced by plant uptake, mineralisation and immobilisation ($NO_3 \leftrightarrow R\text{-}NH_2$), denitrification ($NO_3 \rightarrow$ gaseous N), volatilisation ($NH_4 \rightarrow NH_3$), and nitrification ($NH_4 \rightarrow NO_3$). Most transformations are microbial related, and are thus affected by soil conditions such as moisture availability, oxygen availability, soil carbon, temperature (e.g. Q_{10} principle – denitrification doubles for every 10°C increase in the range of 5–35°C), and soil pH.

We do not dwell on the full scope of soil-nitrogen transformations as NZ pastoral soils are complexed by the addition of high rates of urine-N associated with grazing livestock in situ. Around 80–90% of N ingested by livestock is returned as excreta, mostly as urea in urine, which is rapidly hydrolysed to NH_4 and nitrified to NO_3 under aerobic conditions. The amount of nitrate that is generated – equivalent to 500–1000 kg N/ha/yr for dairy cows (Haynes & Williams 1993) – is far in excess of what plants and soils can assimilate before leaching occurs. Urine patches are thus regarded as the major source of nitrogen losses in grazing systems (Ball & Ryden 1984; Di & Cameron 2002).

Mineralisation can create a large source of soil nitrate when soils are cultivated, while anaerobic conditions for extended periods can have a significant influence on denitrification and losses via gaseous pathways (thereby decreasing NO_3 available for leaching). Infrequent saturation conditions are generally related to soil permeability properties (Section 2.2.2), while extended saturation conditions are a particular feature of soils with gley morphology.

2.2.2 Gley morphology and denitrification

Under saturated conditions, dissolved oxygen in the water becomes exhausted and reducing conditions prevail. Soil in an oxygenated state is normally pigmented in red, brown, or ochreous colours. The pigments are derived from Fe and Al species that occur as stable oxides or hydroxy-oxide minerals. But under reducing conditions the Fe and Al species become mobile, and in areas where they are depleted the soil colour becomes grey. Migration to zones of higher oxygen content allows reversion to stable coloured forms with precipitation as concentrations observed as red or brown mottles. Gley is derived from the Ukrainian 'glei' for sticky blue clay.

Lin et al. (2007) found a strong association between dominant-grey coloured soils and persistent water tables, and mottled soils with seasonal saturation. In an American study, Daniels et al. (1971) concluded that brown mottling indicated saturation through 25% the year, and dominant-grey colours indicated saturation though 50% of the year. Results from a study of English soils (Moore 1971) suggest that soils need not be saturated long periods for gley morphology to develop.

Grey colours and mottles are used in New Zealand (and many other countries) to define soil drainage classes: very poorly, poorly, imperfect, moderately well, and well (Milne et al. 1991). The New Zealand Soil Classification (Hewitt 2010) recognises a mottled profile form which identifies imperfectly drained soils, and a gley profile form which identifies poorly and very poorly drained soils. Drainage classes indicate the depth to the top of a water table, from the ground surface, and its duration. A mottled profile form indicates intermittent water saturation, and a gley profile form indicates prolonged water saturation.

Drainage class has an impact on denitrification rates and the amount of nitrate available for leaching. De Klein et al. (2003) studied nitrous oxide emissions under urine patches for four NZ soils with different drainage classes, and found that nitrous oxide losses were greatest from a poorly drained soil (2.5% of applied urine-N lost), and lowest for a well-drained stony soil (0.3% of applied urine-N lost). These are significant but somewhat modest differences (2.2% difference between well and poor).

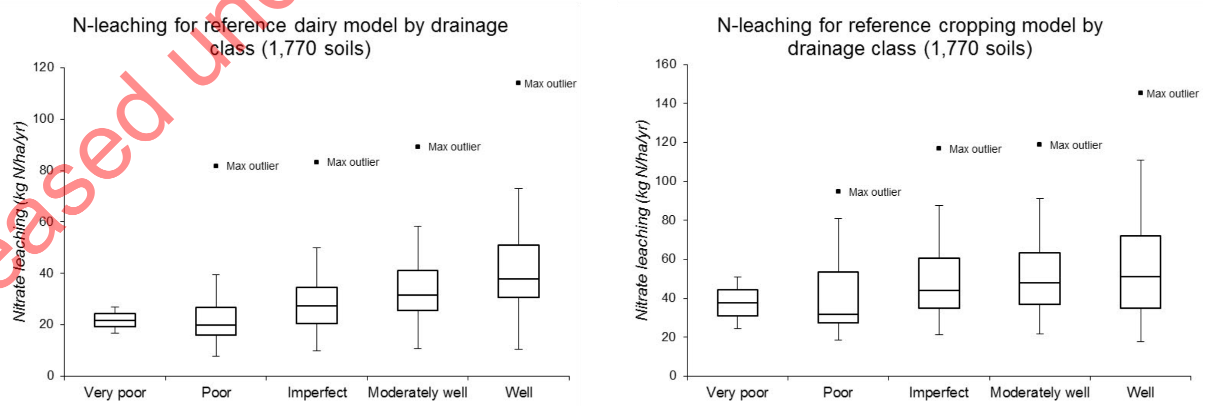

Figure 3 Relative effect of soil drainage class on nitrate leaching for two reference Overseer® farm systems (dairy and cropping) modelled over 1770 soils (dominant S-map siblings). Only two data values are available for very poorly drained soils, which slightly distort the pattern (data from Pollacco et al. 2014).

Increased gaseous losses from denitrification under reducing conditions decrease the amount of nitrate available for leaching. This is demonstrated using the results of Pollacco et al. (2014) who modelled all S-map soils through two reference farm systems (Fig. 3). Only two data values are available for the very poorly drained class, which distorts the pattern (these are usually Organic soils that have only limited observed data available from the National Soils Database), and Overseer® may not fully account for the effects of slow drainage on denitrification (Pollacco et al. 2014). However, based on averages of the poor and well-drained soil classes, there is a potential for 1.9 and 1.5 fold increases in N-leaching for dairy and cropping respectively.

2.2.3 Soil properties and water movement

Soil physical characteristics that determine soil permeability and affect the rate of water movement can have a large influence on nitrate leaching. Permeability is a property determined from the interaction of many other soil characteristics and properties, including (but not restricted to) soil texture, soil structure, water storage capacity, infiltration, porosity (including macroporosity and pore size distribution), bulk density, and hydrophobicity. We single out porosity as a key variable of influence for both permeability (which ultimately determines the rate of water transmission through an unsaturated soil) and water-holding capacity (which determines the volume of water that can be held in a soil before deep drainage and leaching occurs).

Porosity is the fraction of the total soil volume that is represented as spaces between particles (e.g. sand) and soil aggregates; as holes or voids associated with plant roots or burrowing organisms; and as fissures or cracks related to seasonal patterns of wetting and drying (shrinking and swelling). Fundamentally, water flows rapidly through large pores because of gravity and low adhesion,[1] and slowly through smaller pores because of water tension (adhesion forces are greater or similar to gravitational forces). Soils with a high porosity of mostly large pores will therefore drain more rapidly than a soil with an equivalent porosity of mostly small pores (in unsaturated conditions).

Pore space influences the rate of nitrate leaching in several ways. Soils with a high volume of small pores will generally have slow rates of drainage and elevated levels of denitrification. Soils with porosity characteristics that are more conducive towards 'plug flow' (resident soil water is gradually pushed out of the rootzone by incoming surface water) will generally exhibit concentrations of nitrate moving down the profile. Soils with a high volume of large pores have an elevated risk of bypass flow, depending on the source of nitrogen. For example, if nitrogen is present in the infiltrating water (e.g. from effluent, urine, fertigation), or if water is applied immediately after a nitrogen addition (e.g. from urine, fertiliser, effluent), then there is a risk that the nitrogen will pass rapidly down the profile without any attenuation. However, nitrate already in the soil in medium and small sized pores is not affected by bypass flow (in principle).

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[1] Adhesion is the property of a substance, in this case water, to 'stick' to another substance.

Porosity is also strongly related to water-storage capacity, whereby a high volume of appropriately sized pores translates to a greater capacity to store water. Profile Available Water (PAW) is a measure of this capacity, defined as the water stored between field capacity (10 kPa) and wilting point (1500 kPa), summed over the depth from the surface to a depth of one metre (S-map definition). PAW is recognised as having a significant influence on nitrate leaching. For example, Lilburne et al. (2003) modelled nitrate leaching according to soils, climate and management for an irrigated 2-yr wheat rotation. They found that PAW accounted for approximately 25% of the variation in leaching.

Pollacco et al. (2014) modelled all S-map soils through two Overseer® farm systems models. Based on their results, nitrate leaching also exhibits a strong relation with PAW, whereby leaching decreases for soils with a greater capacity to hold water (Fig. 4). Results for dairy are slightly distorted because Overseer® calculates soil water to a 60-mm depth for pasture (and 150-mm for cropping), while the PAW in Fig. 4 is to 100 cm.

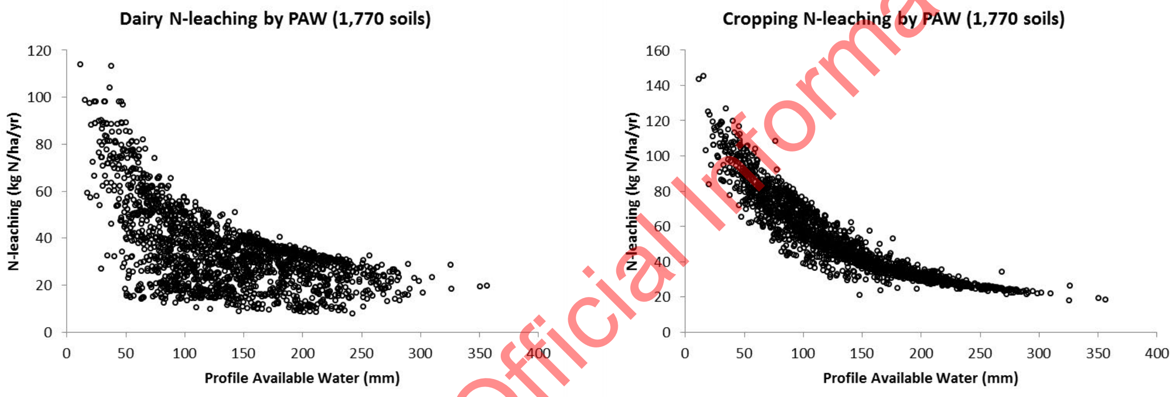

Figure 4 Relationship between N-leaching and Profile Available Water (PAW) to 100 cm for two reference Overseer® farm systems (dairy and cropping) modelled over 1770 soils (data from Pollacco et al. 2014).

2.2.4 N-leaching from different soils under the same conditions

A number of lysimeter and field-based studies have compared leaching losses from two or more soils under the same conditions and treatments (Table 1). While not an exhaustive list, it demonstrates that a difference in soil can result in 1.4- to 3.3-fold differences in N-leaching.

Table 1 Examples of studies comparing nitrate leaching from different soils (where the differences in N-leaching are attributed to soils alone)

Study	**Technique**	**Number of soils**	**Lowest and highest N-leaching by soil**	**Difference factor**
Simmelsgaard 1998	Drained plots	3	26 & 68 kg/ha/yr	x 2.6
Aronsson & Bergstrom 2001	Lysimeter	2	140 & 341 kg/ha	x 2.4
Bergstrom & Johansson 1990	Lysimeter	2	20 & 65 kg/ha/yr	x 3.3
Gaines & Gaines 1994	Leaching cores	4	119 & 173 ppm	x 1.5
Vinten et al. 1994	Drained plots	2	27 & 38 kg N/ha/yr	x 1.4

Modelling allows a greater variety of soils to be examined, including extreme examples that may otherwise never be tested. Figure 5 reports the distribution of N-leaching from two reference farms (dairy and cropping) modelled through Overseer$^{®}$ nutrient budgets (v. 6.1.0) using S-map soils as of May 2014 (2235 unique siblings). Excluding outliers, the results suggest that a change in soil alone has the potential to result in 6- to 8-fold differences in Overseer$^{®}$ estimates of nitrate leaching, for cropping and dairying systems respectively (or 8- to 15-fold differences if outliers are included).

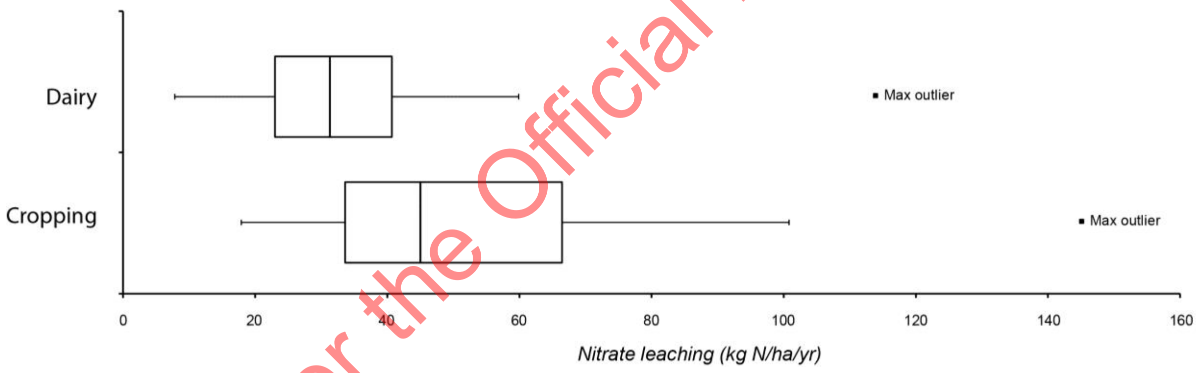

Figure 5 Boxplot distribution of nitrate leaching results for two reference Overseer$^{®}$ models (dairy and cropping) implemented across 2235 S-map soils (data from Pollacco et al. 2014). Soil is the only variable changed. May 2014 version of S-map.

In summary, there is a strong theoretical basis to support the argument that soils and their properties influence nitrate leaching, particularly in regard to soil properties and characteristics that related to permeability, profile water holding capacity, and redox conditions. This is backed by a number of research studies with up to 3-fold differences in N-leaching have been reported for different soils under the same conditions and treatments. Overseer$^{®}$ modelling suggests up to 6- to 8-fold differences are possible with NZ soils. Accordingly, it is both relevant and important that the best possible soil information is integrated into the MfE freshwater model.

3 Objectives

Landcare Research have been contracted to provide soils data and advice towards the development of MfE's freshwater model. Specific objectives include:

- Develop and supply an interim national soil layer (S-map based) with attributes relevant to nitrate leaching.
- Develop and supply a national rating of soil nitrate-leaching potential.
- Provide recommendations and options for integrating soil information into MfE's freshwater model.

4 Methods

4.1 Interim national soil layer

This section provides a description of two soil databases used to create the interim national soil layer, and an outline of the method used to fit the result to a standardised NZ outline based on Statistics NZ datasets.

4.1.1 Description of the S-map soil information system

S-map is NZ's established and most reliable source of soil information, and is widely trusted and used by a diversity of end-users for a wide spectrum of applications. The average usage of S-map online over the last 6 months is over 3000 visits from 1800 unique visitors who downloaded 3500 factsheets each month (Fig. 6). Among other things, the system has been explicitly designed to provide the best possible soils data for modelling, and has recently become the recommended standard for soil parameterisation of the Overseer® model (OMS 2015).

Building a national soil inventory system is not an insignificant undertaking. S-map involves a combination of fieldwork (large areas in NZ have never been properly mapped), validated digital soil mapping where suitable (not all soil-terrains are predictable, especially flat land), and the use of legacy paper soil maps (where they have a high standard of survey quality). S-map's inference engine is used to calculate a range of soil properties using measured data from the National Soils Database, observed functional properties (a critical and unique fieldwork component of Smap) and validated, peer reviewed statistical relationships.

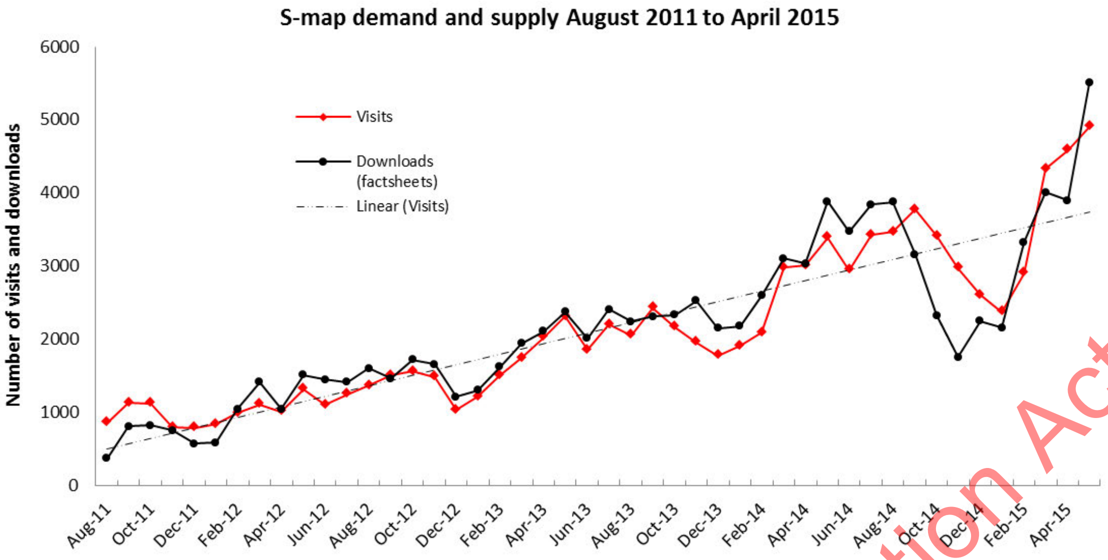

Figure 6 Demand and supply of S-map, August 2011 to April 2015.

The principle units of S-map are the soil *family* and *sibling*. Each soil family is defined as a unique combination of attributes (NZSC classification, parent material, rock type, dominant texture, and permeability class). Soil classes are further characterised as siblings according to their depth to rock class, stoniness, land type, drainage, texture (more detailed), functional horizons and miscellaneous variant information. The uncertainty of each of these family and sibling attribute classes is specified.

Each sibling is populated with field-determined base data (base properties), including depth, depth to slowly permeable layer, rooting depth, rooting barrier, horizon thickness, stoniness, clay and sand content. Additional derived properties include modelled estimates of available water (mm), macroporosity, water retention, bulk density, carbon, nitrogen, phosphorus, calcium, cation exchange capacity, pH, and phosphorus retention. Considerable effort is also invested in generating soil qualities of immediate relevance to end-users, such as dairy effluent risk, N & P leaching vulnerability, and risk of soil structural damage associated with pugging. In effect, the S-map engine can deliver a range of soil information relevant to water quality that can be readily customised for specific applications and models (a key strength).

4.1.2 Description of Fundamental Soil Layers (FSL) database

The Fundamental Soil Layers (FSL) represents Landcare Research's first attempt to create a spatial soils-database to support GIS and modelling (Barringer et al. 1998). However, while appropriate for the time, the methodology was largely constrained by the reference datasets and technology available at the time. Consequently, the FSL is gradually being retired in favour of S-map (which is considered to contain better quality and more reliable data). However, there is not yet national coverage for S-map, so the FSLs are still used on occasion but with recognition of limitations.

The FSL database contains spatial information for 16 key attributes: slope, potential rooting depth, topsoil gravel content, proportion of rock outcrop, pH, salinity, cation exchange capacity, total carbon, phosphorus retention, flood interval, soil temperature, total profile available water, profile readily available water, drainage, and macropores (shallow and deep). These layers were generated by creating regional legends which were correlated using the New Zealand Soil Classification (NZSC), referenced to the National Soils Database (NSD) and other relevant data sources.

The spatial representation of soils in the FSL has been derived from the 1:50 000 scale NZ Land Resource Inventory (NZLRI), which is not a soils database. Rather, the NZLRI is a land resource database containing an inventory of five physical factors (rock type, soil, slope, present type and severity of erosion, and vegetation) and a Land Use Capability rating (LUC). Soil is one of the five recorded factors, but the definition and delineation of polygon units was based on the combination of all five factors. In short, NZLRI units are not soil units, and do not therefore represent the spatial distribution of individual soils.

Another key limitation is how the NZLRI soil factor was derived. Rather than conventional soil survey, the NZLRI was populated using soil names from already published surveys. In many areas soil surveys at a comparable or more detailed scale did not exist, and gross interpretations of far coarser scale surveys were made. Only approximately 18% of the NZLRI has soils drawn from comparable scale surveys (1:63 360 or more detailed), while the greater extent (82%) is based on much generalised information (Fig. 7).

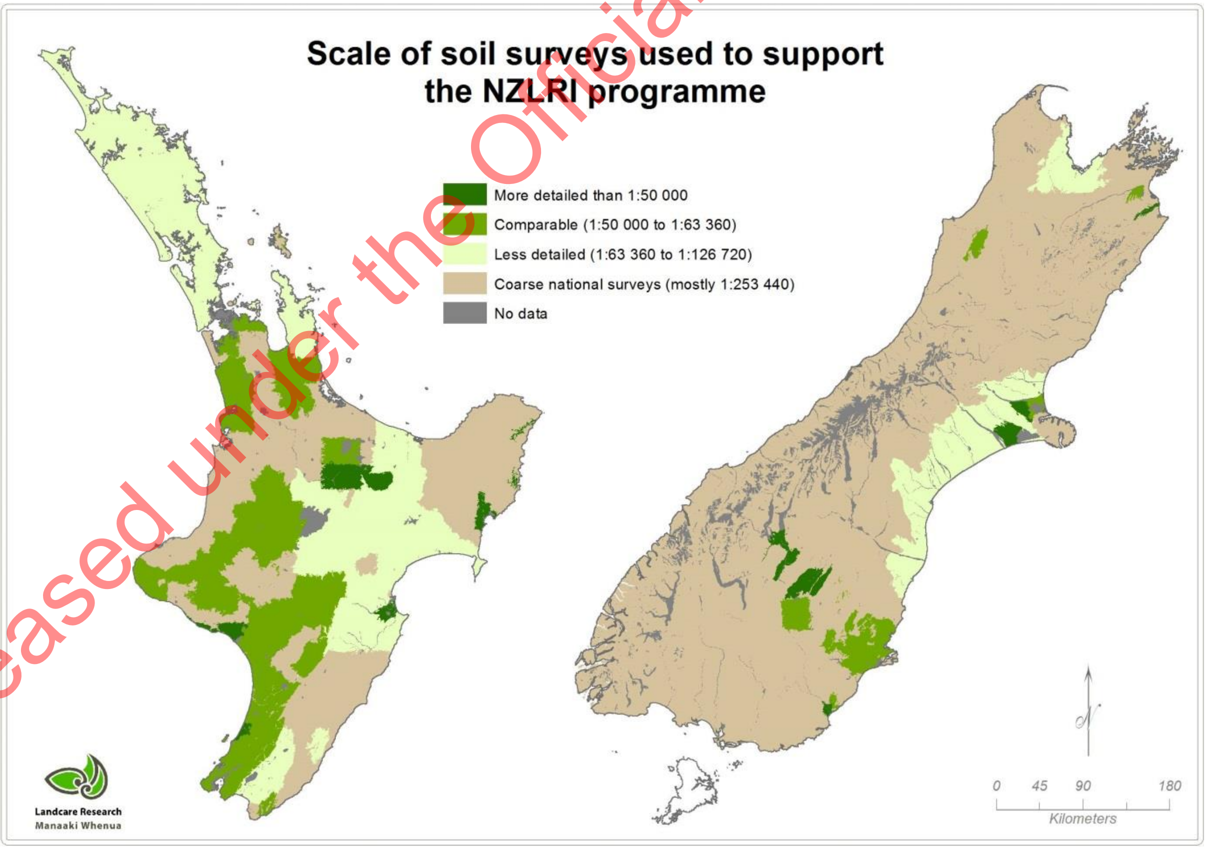

Figure 7 Scale of surveys used in the NZLRI and FSLs databases. Areas other than green represent very high uncertainty regarding soil information in the FSLs.

4.1.3 Hybridisation to a common geographic boundary

All dataset boundaries are standardised to a common NZ outline to ensure data consistency. We have chosen the Statistics NZ high resolution geographic boundary for regional authorities[2] dissolved to create a single boundary outline. In principle, this boundary should match meshblocks, territorial authorities, wards, and several other Statistics NZ datasets. Total resulting area is 268 107 km^2 (including Chatham Islands). This boundary also appears to match LINZ cadastral parcels, but not LINZ's 1:50 000 scale topographic coastline (which has a slightly different area of approximately 268 186 km^2). We expect our result will match the farms and parcels used in the freshwater model (all of which are derived initially from LINZ cadastral parcels).

Neither the FSL nor S-map currently matches the Statistics NZ geographic boundary. This is addressed as the hybrid database is prepared. Both datasets were firstly clipped to the new NZ outline, and the FSLs were subjected to further processing to extend FSL polygons out to the new boundary. The S-map layer was then appended into the new hybrid layer, with any slivers (polygon fragments) along the S-map/FSL boundary cleaned by aggregating them into the polygon with the longest shared boundary. The resulting intermediary layer has three unique identifiers (S-map id, FSL id, and a new hybrid id), which are used to link in attributes from the original databases.

4.1.4 Confidence and quality evaluation

S-map has an in-built level of confidence calculated from estimates of uncertainty made during field survey and applied to parameters during data entry. An overall indication of confidence is assigned to map unit composition, whereby each sibling is assigned a confidence rating of High (H), Medium (M) or Low (L):

- High and Medium indicates confidence in the proportional value of a soil sibling (or functionally similar siblings) occurring within the map unit.
- For a High confidence map unit with a single sibling, the sibling should be found in at least 80% of the map unit (i.e. 100±20), as opposed to at least 60% (i.e. 100±40) in a Medium confidence map unit.
- For a double symbol map unit it is likely that areas for both siblings will be within ±10 in a High confidence map unit, and ±20 in a Medium confidence map unit.
- A rating of L (Low) is used where the pedologist has less confidence in the identified sibling or its proportion due to lack of data or insufficient resources to verify the data. This will usually occur where the sibling(s) have been assigned based on a soil-landscape relationship and aerial photo interpretation, rather than a site visit with direct observation (auger holes or soil profile descriptions).

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[2] http://www.stats.govt.nz/browse_for_stats/Maps_and_geography/Geographic-areas/digital-boundary-files.aspx

A similar system of confidence cannot be applied the FSLs because the required information was never collected during the original surveys. Some inferences can be made from the soil surveys and information used to populate the NZLRI (Fig. 7), and the FSL includes a source-based estimate of quality for value attributes (Table 2).

Table 2 Source and quality rating for FSL numerical variables (Newsome et al. 2008)

Code	Source/quality
m	From analyses or measurements of the named soil
r	Estimated from relationships with other soils, but the estimate is considered to be valid
u	Estimated from relationships with other soils, but with an unknown accuracy level
uf	Estimated from General Soil Survey data (coarse scale; least reliable)
p	Deduced from soil profile morphology (used only in the South Island)

The codes in Table 2 describe how the attributes were populated, with origin determining quality. Code *m* has the highest quality, and indicates a direct match to a soil in the NSD with good observed data. Code *r* is similar in that soils assigned this code have characteristics that make them very similar to a soil recorded in the NSD. The remaining codes effectively signal educated guesses (P Newsome, Landcare Research, pers. comm., 20 June 2015).

If codes *m* and *r* correspond with soil surveys at scales more detailed than 1:63 360 (previous Fig. 7), we have assigned a High confidence to the FSL data. For all other codes (*u*, *uf*, *p*) we assign Very low confidence, primarily because of their limited robustness in terms how they were estimated, but also because they have low levels of accuracy when compared against S-map (discussed in the next paragraph). These two ratings are combined with S-map confidence levels to provide an estimate of confidence for the entire layer.

In addition we have undertaken a comparison between S-map and the FSL where the two databases share a common area (excluding 'no data' classifications). Purpose is to evaluate how well the FSL NZSC matches S-map at three levels of the NZSC (Order, Group, and Subgroup). Metrics used include confusion matrices and the kappa statistic, calculated for both *classification accuracy* and *map accuracy*, and *corresponding percent area* (percent of matching NZSC by area).

A confusion matrix is a table that maps the degree of match between two datasets with the same categorical variables. Each column of the matrix represents the instances in a predicted class (i.e. in our case FSL NZSC), while each row represents the instances in an actual class (i.e. S-map NZSC). How well the instances match can be evaluated using several different metrics, but here we restrict our evaluation to Total Accuracy because of the large number of classes involved.

The kappa statistic (Cohen 1960) is also a measure of agreement between categorical variables, but differs in that it takes into account random chance, which generally means it is less misleading than simply using accuracy as a metric.

Corresponding percent area was calculated by intersecting the FSLs with S-map and then calculating the total area of all polygons with a matching classification. *Classification accuracy* is a measure of how well the soil classifications match between databases (effectively aspatial), and was calculated by converting the intersecting polygons to points (one point per intersected polygon; 429 730 points). *Map accuracy* is a measure of accuracy for the entire layer (i.e. is spatial), and was calculated from a sample of 928 774 randomly generated points (one million points less those that intersected with 'no data' polygons). This represents a sampling density of one point per 7.5 ha, which is denser than the 25 observations per hectare recommended for a 1:50,000 scale soil survey (Forbes et al. 1982), and well in excess of a representative sample size calculated at the 0.95 confidence level for 256 NZSC subgroup classes according to the guidelines of Congalton and Green (1999). Confusion matrices and kappa are calculated according to Rossiter (2014).

4.2 Soil nitrate leaching potential

The nitrate leaching vulnerability index of Webb et al. (2010) is used to provide an estimate of national soil nitrate-leaching potential. Index classifications are evaluated against Overseer® N-leaching results of Pollacco et al. (2014), and we undertake a brief review of alternative indices and models.

4.2.1 Nitrate leaching vulnerability index

The nitrate leaching vulnerability index (Webb et al. 2010) was developed for Environment Canterbury to map the likelihood that soils would leach nitrate a soil (to a maximum of 1m depth). The focus was on leaching at a generalised scale of 1:50 000 scale, to enable understanding of the distribution of probable N leaching across the region.

A vulnerability model differs from a risk model. Risk takes into account the pressure of the land use, in this case the grazing intensity and land management practices, and the consequence of the risk being realised. Vulnerability, however, does not consider the pressure – the purpose is to evaluate only the effects of soil characteristics on nitrate leaching – and better understand the soil resource. The model is similar to that developed by the same authors and used as part of the CLUES water quality model (Elliot 2008).

Environment Canterbury's purpose was to develop a standard methodology that could be used to define zones with varying likelihood of nutrient and microbial contamination to waterways. These zones then could act as a basis for setting nutrient load limits across a catchment and targeted management of non-point-source discharges, including setting aside vegetated buffer zones to trap contaminants in overland flow (Webb et al. 2010).

The vulnerability rating is based on the capacity of the soil to store water (profile available water capacity) and the attenuation of nitrogen through denitrification associated with anaerobic conditions (after Woods et al. 2006).

Very low vulnerability to nitrogen leaching is confined to poorly drained soils that have significant attenuation of nitrogen through denitrification (Organic and Gley Soils). Small areas of shallow, poorly drained soils qualify for low vulnerability. The remaining soils vary from low to very high leaching vulnerability according to soil depth and texture – deep loamy soils having low vulnerability grade to very stony-sandy soils with very high vulnerability.

The index is calculated according to Equation 4.1, whereby N_v is the unclassified nitrate leaching vulnerability index, PAW_x is the profile available water factor (Table 3), and DN_x is the denitrification attenuation factor (Table 4).

$$N_v = PAW_X \times DN_X \tag{4.1}$$

PAW ranges were selected to reflect sensitivity to leaching (Webb et al. 2010). There is low sensitivity to leaching above 100 mm PAW so a large class is given to encompass soils from 100 to 150 mm PAW. The lowest class (PAW < 40 mm) is selected to capture soils with very low PAW. Last, two classes were selected to capture variation in leaching potential between 40 and 150 mm PAW.

Table 3 PAW ranges (mm) and corresponding PAW_x factors

PAW (mm)	**PAW_x**
<40	2
40–69	1.8
70–99	1.5
100–150	1.2
>150	1

Table 4 Denitrification attenuation factors for different soils

Soil class	**DN_x**
Organic Soils or soils with an impermeable layer	0.3
Remaining very poorly drained soils	0.5
Poorly drained soils and downland soils with a fragipan	0.7
All other soils	1

Denitrification attenuation factors (Table 4) are related to biochemical soil reduction as indicated by poor soil drainage or the presence of organic soil materials (Webb et al. 2010). The degree of denitrification is estimated by the presence of Organic Soils (permanent high water table and high organic matter), very poorly drained and poorly drained soils. Downland landscapes that have thick loess mantles contain soils with impermeable fragipans that greatly restrict drainage. On these landscapes, excess water is transmitted laterally into poorly drained hollows where denitrification will be active. Downland landscapes therefore qualify for an attenuation factor equal to poorly drained soils. Resulting index values are classified into five classes (Table 5).

Table 5 Nitrate leaching vulnerability classes

Vulnerability class	Vulnerability code	Vulnerability index range	Main Canterbury soils
VH	1	1.75 – 2.0	Very stony Brown and Pallic Soils, stony and very stony Recent Soils, soils that are shallow over rock
H	2	1.4 – 1.75	Shallow and stony Pallic and Brown Soils, deep sandy Raw Soils
M	3	1.0 – 1.4	Moderately deep Brown or Pallic Soils, deep sandy soils
L	4	0.85 – 1.0	Deep Brown, Melanic, Pallic, shallow Gley Soils
VL	5	0.3 – 0.85	Organic and Gley Soils

The index is applied to both the FSL and S-map databases for comparative purposes. PAW in the FSL is to 900 mm and thus differs from PAW in S-map, which is calculated to 1000 mm. FSL PAW is corrected where there is no impermeable layer according to Equation 4.2, which takes into account the higher water holding capacity of topsoil per unit depth.

$$PAW_{1000} = \left(\frac{Tr \times PAW_{900}}{Td \times 900} \times Td_{1000}\right) + \left(\frac{Sr \times PAW_{900}}{Sd \times 900} \times Sd_{1000}\right) \tag{4.2}$$

Where PAW_{1000} and PAW_{900} are profile available water to depths of 1,000 mm and 900 mm respectively, Td and Sd are topsoil and subsoil depth coefficients of 0.2 and 0.8 (based on an assumption that 20% of the soil profile is topsoil), Td_{1000} and Sd_{1000} are topsoil and subsoil depths for a 1000 mm profile using the 0.2 and 0.8 depth coefficients (i.e. 200 mm and 800 mm), and Tr and Sr are topsoil and subsoil PAW coefficients that allocate a larger PAW to the topsoil in recognition that the topsoil generally holds more water. PAW coefficients based on approximate topsoil and subsoil available water-holding capacities for 7 soil Orders (McLaren & Cameron 1996) are calculated as 0.31 and 0.69 for Tr and Sr, respectively. For example, if PAW_{1000} = 200 mm, there will be 62 mm of PAW estimated for the top 200 mm (3.1 mm PAW for every 10 mm depth) and 138 mm of PAW estimated for the lower 800 mm (~1.7 mm PAW for every 10 mm depth).

4.2.2 Confidence and quality evaluation

Two comparisons are undertaken. First, the accuracy of FSL N-leaching vulnerability is evaluated by comparing the results of FSL vulnerability to S-map vulnerability, using confusion matrices, kappa, and corresponding percent area (described in Section 4.1.1). The comparison is performed across 7 million hectares where both the FSLs and S-map overlap (excluding 'no data' areas). The degree of agreement will provide an indication of confidence for the non S-map component of the hybrid dataset (i.e. where the FSLs are used to calculate N-leaching vulnerability).

Second, we compare S-map N-leaching vulnerability to modelled nitrate leaching results to provide an indication of index performance relative to modelled N-leaching results. To achieve this we compare S-map N-leaching vulnerability classifications to the Overseer® N-leaching results for 1770 soils (dominant siblings) of Pollacco et al. (2014).

4.3 Alternatives for nitrate leaching potential

We have undertaken a brief review of the many different approaches used to evaluate nitrate leaching potential (separate report available on request). This is used to make suggestions for alternatives or improvements to the N-leaching vulnerability index.

4.4 Integrating soil information into the freshwater reporting model

The freshwater model is being developed to provide statistically robust indicators of diffuse-source contaminants to freshwater. It involves a new national modelling framework still under development, and draws upon a number of sensitive Government datasets that strongly influence both methodology and the type of results that can be published.

The authors have not been directly involved in model development, and have not examined the data with any appreciable degree of scrutiny. However, a key objective is to provide advice on how soil data may be integrated into the freshwater contaminants model. To facilitate this, we have attempted to detail the model structurally, especially with respect to Stage 2. We acknowledge that the model is in a state of development, and that our description of the model may therefore be subject to refinement. We offer options for integrating soil information at several points within the freshwater model process.

5 Results

5.1 Interim national soil layer

S-map coverage as of June 2015 has been combined with FSL coverage and adjusted to a standardised boundary based on Statistics NZ geographic data. Approximately 28% of the resulting hybrid soil map is S-map (Fig. 8).

- S-map (June 2015) currently covers 7.5 M ha (28% of the hybrid layer). Coverage is greatest for the intensively farmed lowlands (4.4 M ha representing 59% of current S-map coverage, and representing 51% of NZ's lowland areas < 7° slope).
- For current S-map coverage, approximately 44% of dominant soil siblings have Low confidence, 41% have Medium confidence, and 14% have High confidence.
- Combined with the FSLs, confidence for the entire hybrid database is 6% High, 12% Medium, 11% Low, and 70% Very Low (for FSL data based on estimates from coarse soil surveys).

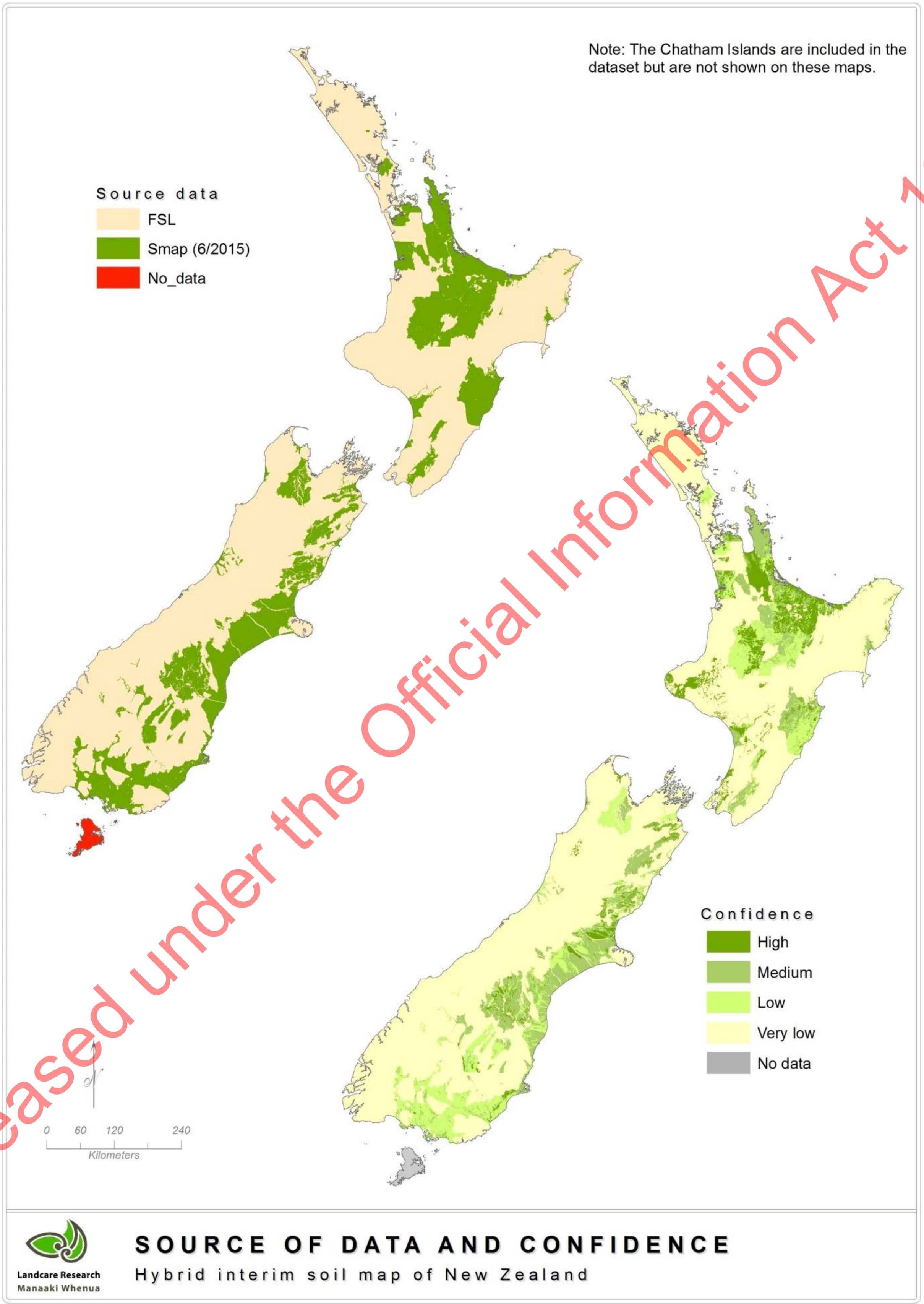

Figure 8 Source data and confidence of the hybrid interim national soil map.

Inconsistencies were encountered with the NZ boundary created from NZ Stats geographic data. Parts did not produce a good representation of the NZ coast. For example, we encountered inland 'holes' after the dissolve process, and second, areas off the Fiordland coast were generalised (Nancy, Charles, Caswell, George Sounds are included as land mass, while islands such as Anchor, Long, and Cooper are omitted). However, this is likely to be generalisation associated with the cadastral data itself, and thus the layer remains likely to be a good spatial match with databases being used to the build the freshwater model.

5.1.1 FSL accuracy relative to S-map (NZSC)

An indication of FSL accuracy is calculated using three levels of the NZSC where S-map and the FSL overlap, using Total accuracy (from confusion matrices), kappa and corresponding percent area (Table 6).

The FSLs have modest levels of *classification* accuracy relative to all levels of S-map NZSC, and particularly low accuracy at the most detailed subgroup level (only 17% of the 429 730 intersected polygons had a matching classification). Classification kappa is similarly low, with only slight agreement at the group and subgroup level, and fair agreement at the order level (using the kappa interpretation ranges of Landis & Koch, 1977).

Total *map* accuracy is higher, with 32% of the area having matching subgroups, 44% having matching groups, and 62% having matching orders (Fig. 9). The same values for total accuracy and percent area suggest that the density of random points provides an adequately representative sample, and thus adds weight to the validity of the map accuracy kappa results. A kappa value of 0.30 for the subgroup level is regarded as fair, while values of 0.44 and 0.54 for group and order, both qualify as indicating moderate levels of agreement. However, none of these results would be interpreted as being indicative of a substantial agreement (i.e. kappa > 0.60). Based on results for the most detailed level (subgroup), confidence in FSL as a reliable soil map would be low (relative to S-map).

Table 6 FSL accuracy relative to S-map for three levels of the NZ Soil Classification

NZSC level	**Classes**	**Classification accuracy**		**Map accuracy**		**% area matched**
		Total accuracy	**kappa**	**Total accuracy**	**kappa**	
NZSC subgroup	226	0.17	0.13	0.32	0.30	32%
NZSC group	63	0.25	0.18	0.44	0.41	44%
NZSC order	15	0.46	0.30	0.62	0.54	62%

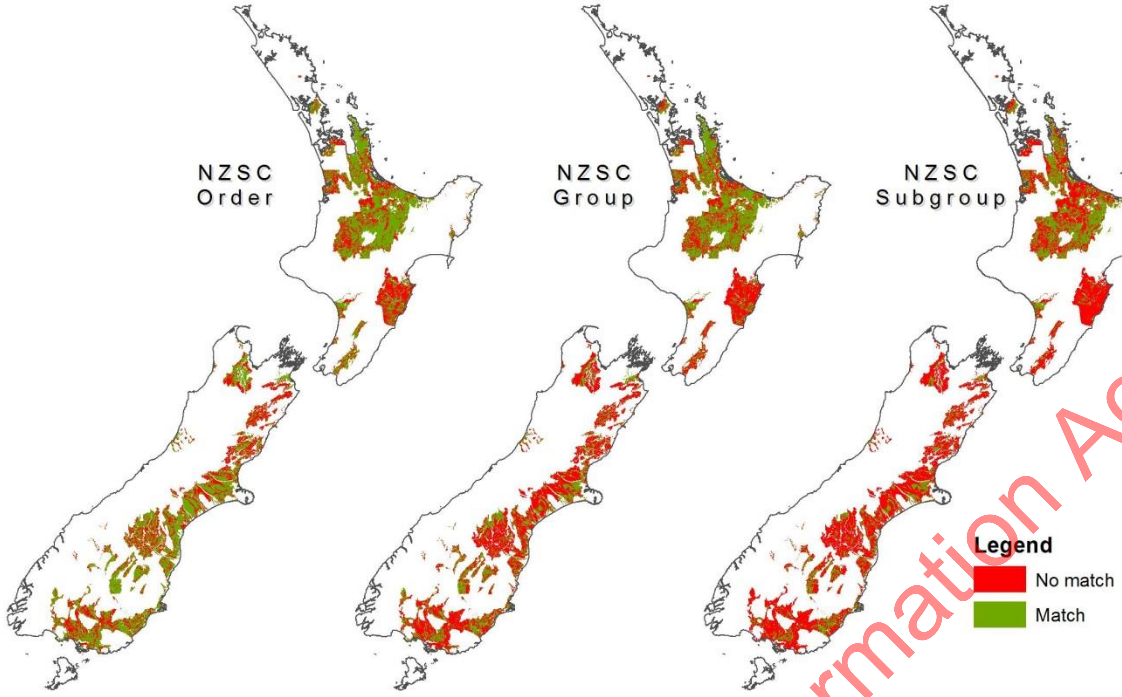

Figure 9 Spatial representation of how well the FSLs match S-map NZSC levels.

5.1.2 Options for improving the accuracy of the hybrid soil layer

Below we offer several options for improving the accuracy of the hybrid soil layer. Emphasis is on targeted mapping of flat lowlands as Digital Soil Mapping (DSM) techniques are being developed for hill country:

- Translate FSL soils into a quasi-Smap framework (separate from the main S-map database) by referencing the original soil profile descriptions and interpreting these into functional horizons and S-map equivalents. A similar exercise has recently been undertaken by Trevor Webb (Landcare Research) for remaining Canterbury lowland soils, including some correction of line work. This is likely to be quicker than the standard S-map process, yet still time-consuming and expensive, given the area that still needs to be mapped. Further, the result will be of a lower standard relative to normal S-mapping (as demonstrated in this report the FSL soil classes are not particularly accurate). While possibly a cost-effective option, we believe any such investment would be better directed at accelerating the normal S-map programme towards the capture of higher quality data.
- Integrating remaining legacy soil maps at equivalent scales into the S-map database. Approximately a further 1 M ha of flat lowlands could be added relatively quickly to S-map using this approach (Fig. 10). Further work is required to determine if these legacy surveys are of sufficient quality, however. This option would facilitate the acceleration of S-map but will not achieve complete lowland coverage.
- Support the acceleration of the existing S-map programme through membership and contribution to the S-map senior-level Funders Group.

5.1.3 Access to the hybrid soil map

Due to the size (756 Mb) the layer is made available for download from Landcare Research's FTP site at ftp://ftp.landcareresearch.co.nz/MfE_soils/ (as a zip file named MfE_soil_layer.zip).

The layer is supplied as an ESRI shapefile in NZTM coordinate space. Attributes included are listed and described in Table 7. Included are unique IDs for linking back to both S-map and the FSLs for further processing or future updates if needed.

Table 7 Attributes in the national hybrid soil layer

Field	Description
Uq_FSL_id	Unique identifier for linking back to the original FSL database
Uq_SMAP_id	Unique identifier for linking back to the original S-map data (June 2015)
Geo_ha	Geographic hectares
Source	Database origin. Areas without soil information (e.g. Stewart Island) are assigned No data
NZSCm	NZ Soil Classification Codes (from Hewitt 2010)
CONFm	Confidence estimates
VULNm	Nitrate leaching vulnerability index classifications (see previous Table 5)
Drain_m	Soil drainage categories
PAW_m	Profile available water to 1 m depth
REGC2015_N	Regional council names

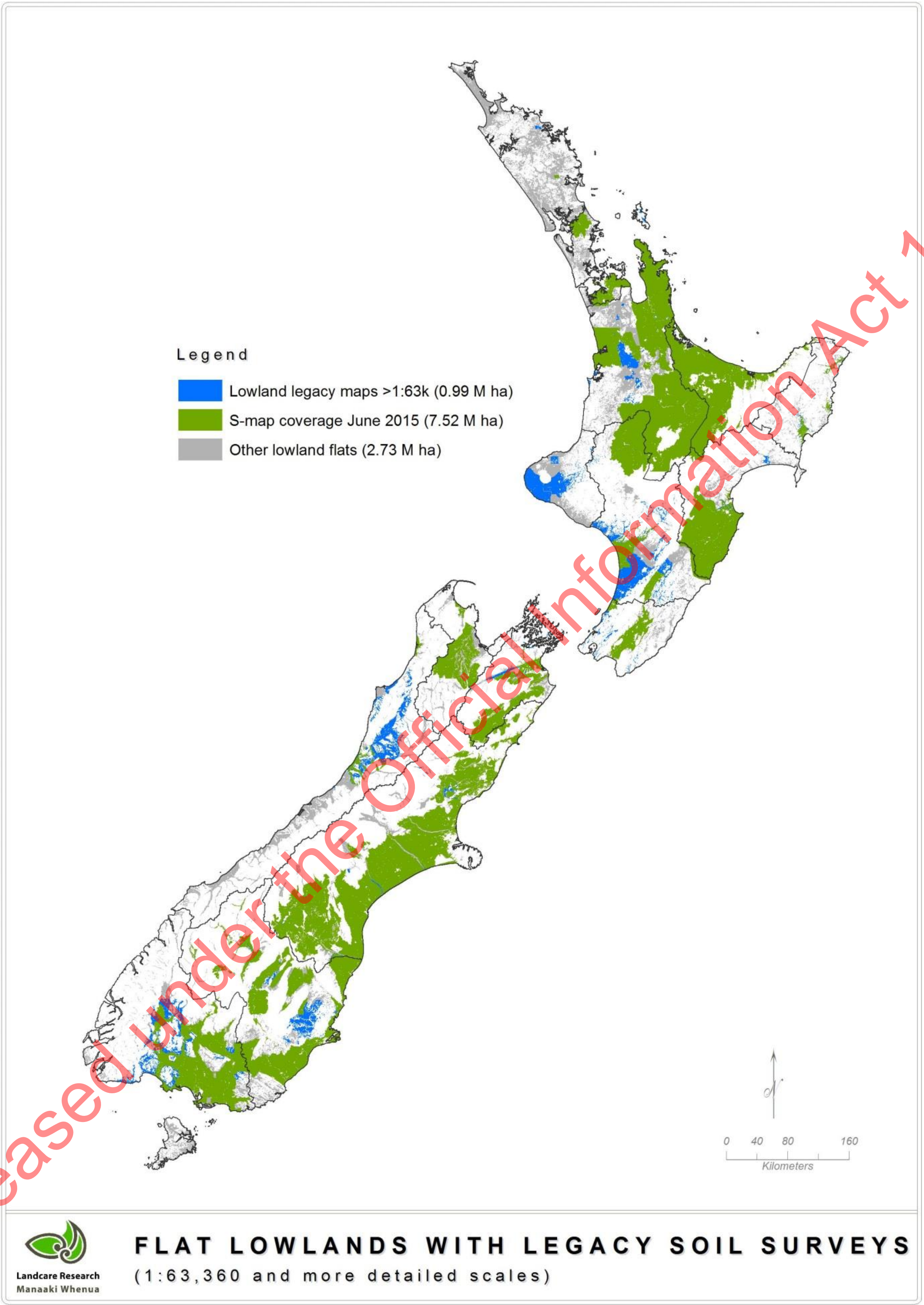

Figure 10 Flat lowland areas that have legacy soil surveys at scales of 1:63 360 and more detailed that have not yet been S-mapped.

5.2 Soil nitrate leaching potential

Results are summarised by regional authority as Table 6. On average, approximately 31% of NZ qualifies as having soils with low risk (VL and L combined), and approximately 41% have an elevated risk (H and VH combined). Regions that stand out as having an elevated risk (H and VH combined > 40% of region) include all the South Island regions, acknowledging that a large component of this includes mountain lands (Fig. 11). Hawke's Bay is the only North Island region that stands out has having a similar level of soil nitrate leaching risk.

Table 8 N-leaching vulnerability summary by regional authority

Region	Hectares							Percent of region					
	VL	L	M	H	VH	No data	Total	VL	L	M	H	VH	No data
Northland	159879	547104	87121	203415	77365	176151	1251035	13%	44%	7%	16%	6%	14%
Auckland	21682	157135	92829	79929	15437	127072	494084	4%	32%	19%	16%	3%	26%
Waikato	233610	982312	509348	373078	224691	134783	2457822	10%	40%	21%	15%	9%	5%
Bay of Plenty	37117	767522	296902	30912	63136	32460	1228048	3%	62%	24%	3%	5%	3%
Gisborne	16246	734517	40844	2238	29812	14994	838652	2%	88%	5%	0%	4%	2%
Taranaki	32089	345191	196293	90408	23282	38170	725433	4%	48%	27%	12%	3%	5%
Hawke's Bay	112885	366180	267769	494051	128871	49374	1419130	8%	26%	19%	35%	9%	3%
Manawatu-Wanganui	157419	566592	894408	305119	246740	51770	2222048	7%	25%	40%	14%	11%	2%
Wellington	44282	55546	414537	63484	180529	53572	811952	5%	7%	51%	8%	22%	7%
Marlborough	12225	35383	212564	233699	400448	152727	1047046	1%	3%	20%	22%	38%	15%
Nelson	78	2059	3656	28477		8171	42442	0%	5%	9%	67%	0%	19%
Tasman	16477	136408	202684	437966	122403	49037	964975	2%	14%	21%	45%	13%	5%
Canterbury	161625	283879	716664	1253553	1652822	452250	4520794	4%	6%	16%	28%	37%	10%
Otago	111489	910011	407553	762446	818009	180990	3190498	3%	29%	13%	24%	26%	6%
West Coast	122731	135698	385936	1139738	217265	330638	2332006	5%	6%	17%	49%	9%	14%
Southland	204507	774357	438524	537460	649070	580201	3184120	6%	24%	14%	17%	20%	18%
Area Outside Region						80834	80834	0%	0%	0%	0%	0%	100%
Total NZ	1444342	6799896	5167633	6035973	4849880	2513193	26810917	5%	25%	19%	23%	18%	9%

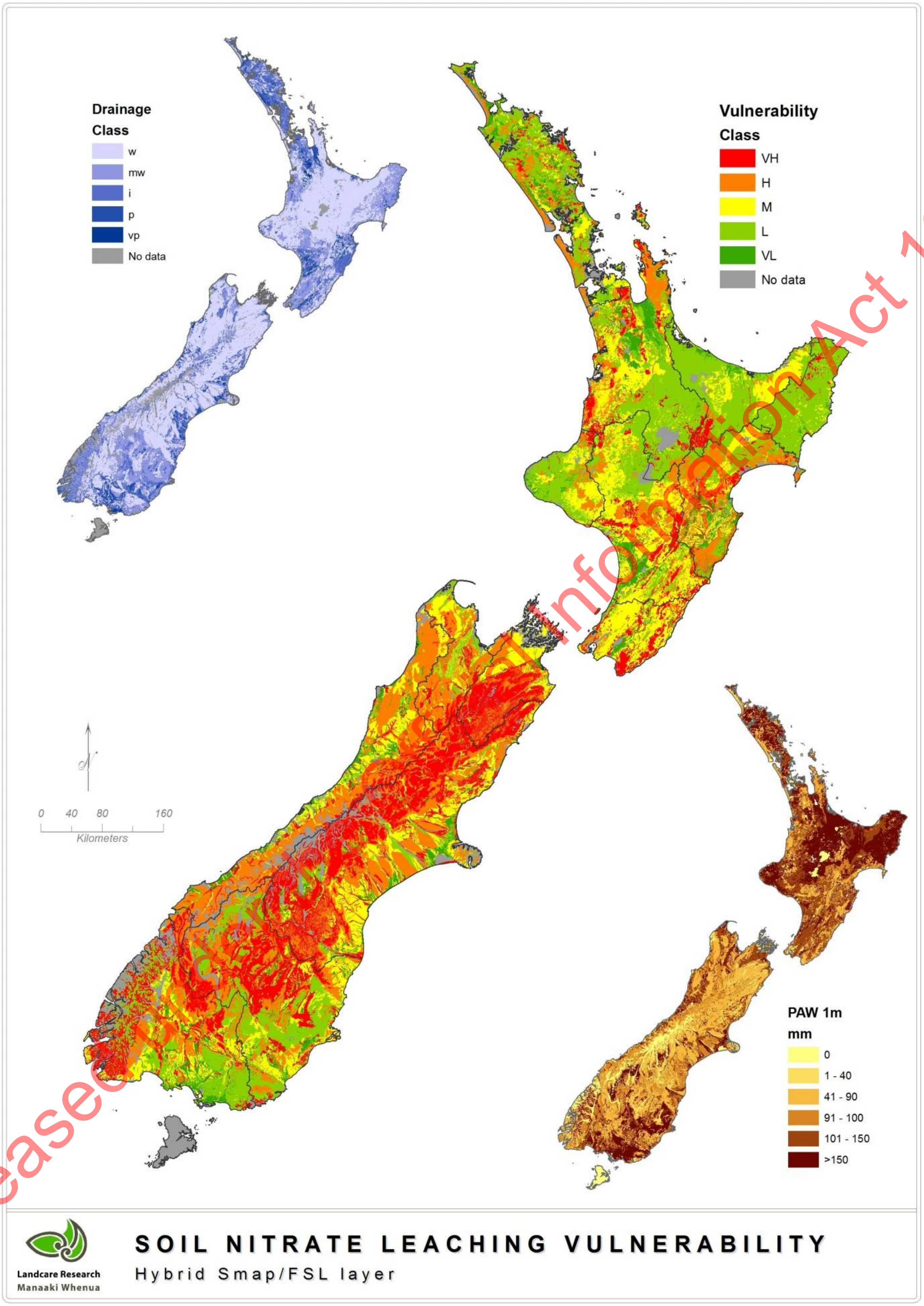

Figure 11 Soil nitrate leaching vulnerability for NZ.

5.2.1 FSL accuracy relative to S-map (N-leaching vulnerability and drainage)

The accuracy of FSL N-leaching vulnerability and drainage has been evaluated by how well the classifications match where the FSLs and S-map overlap (Table 7). Total *classification* accuracy is good for drainage (68% of the 429 730 intersected polygons had a matching classification) and poor for N-leach vulnerability (32% of polygons matched). The kappa statistic suggests only a slight level of agreement for both N-leach vulnerability and drainage.

Total *map* accuracy is higher, with 65% of the area matched for drainage, but only 42% for N-leach vulnerability (Fig. 13). A kappa value of 0.39 for drainage is regarded as fair to moderate, while 0.25 is fair. Neither would be interpreted as a substantial agreement (i.e. kappa > 0.60). Based on these results, confidence in FSL N-leaching vulnerability estimates would be low to very low.

Table 9 FSL accuracy relative to S-map, for drainage classes and soil nitrate leaching vulnerability

Variable	**Classes**	**Classification accuracy**		**Map accuracy**		**% area matched**
		Total accuracy	**kappa**	**Total accuracy**	**kappa**	
Drainage class	5	0.59	0.19	0.65	0.39	65%
N leaching vulnerability	5	0.32	0.12	0.42	0.25	42%

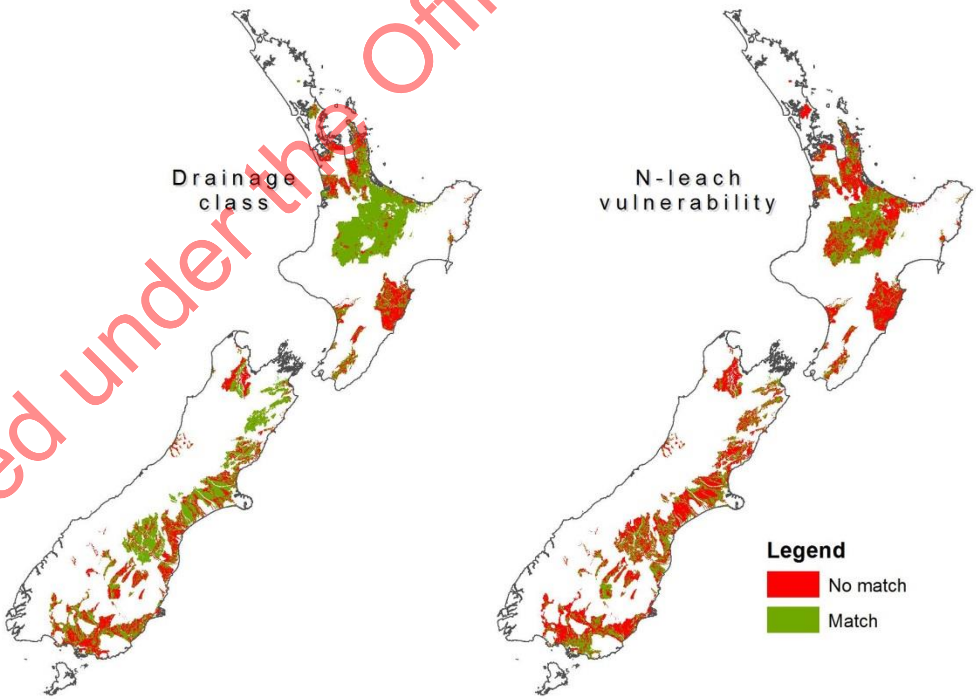

Figure 12 Spatial representation of how well the FSLs match S-map drainage and N-leaching vulnerability.

5.2.2 Comparison of S-map N-leach vulnerability to Overseer®

If soil N-leaching vulnerability is classified as low, then it is reasonable to expect modelled nitrate losses for that soil will also be low (relative to N-leaching from other vulnerability classifications). S-map vulnerability classes are compared with Overseer® N-leaching estimates for two farm systems using the data of Pollacco et al. (2014). Results are presented as boxplots by vulnerability class (Fig. 13).

There appears to be strong agreement and pattern for cropping for all vulnerability classes other than VL. Likewise, there is a general pattern of increasing N-leaching by increasing vulnerability with dairy, although a similar disconnect is evident at the lower vulnerability ratings. In part this is explained through the strong relationship with PAW for M, H and VH vulnerability. For L and VL we do not expect much difference in PAW in the top 600 mm (which is the root-zone depth that Overseer is modelling to). Overall, however, the result appears to demonstrate both a trend and a strong relation between leaching vulnerability and modelled nitrate leaching.

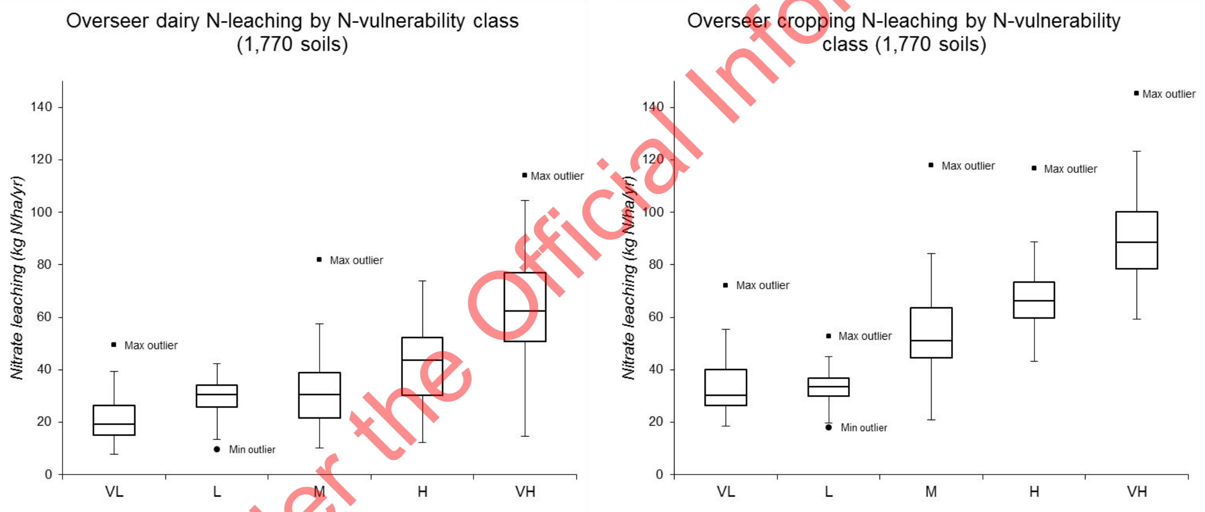

Figure 13 Boxplot distribution of Overseer nitrate leaching for two farm systems (dairy and cropping) by nitrate leaching vulnerability classes (data from Pollacco et al. 2014).

5.2.3 Critique of the soil N-leaching vulnerability index

The N-leaching vulnerability achieves a good to very good match with Overseer®, but not a perfect match at lower vulnerabilities. Key aspects of the index that could be developed to improve accuracy include:

- Bypass flow is currently omitted from the index. Soils with high porosity or a propensity to fracture in dry conditions have a recognised potential to facilitate rapid removal of nitrate to lower horizons (consider a urine event on a cracked soil). However, bypass flow may be partly accommodated by PAW (e.g. sandy soils high macroporosity but already accounted for in having low PAWs), so further investigation is required to justify its inclusion in the index. Modification to include the variable is not an onerous task, but careful consideration and testing is required to ensure a valid weighting.

- The index provides a vulnerability rating only for soil – climate and management factors that influence the amount and timing of drainage losses from the root zone are not considered, although PAW will account for some of the effect. Including a climatic dimension or irrigation information will change the index definition and likely diminish its simplicity, but may result in improved classifications.
- Drainage losses from the rootzone can be readily estimated by implementing a spatial water balance. For example, the lead author of this report developed a national spatial water balance (daily time-steps) that was used to estimate nitrous oxide emissions from dairy land (van der Weerden et al. 2014), while another Landcare Research scientist developed a similar spatial water balance for *Pinus radiata* (Palmer et al. 2009). Furthermore, there are currently two live initiatives within Landcare Research that are spatializing more sophisticated process-based soil water models (WatYield and APSIM SWIM), which are made possible by a third project that has successfully ported S-map data for automatic use within both models.
- To a lesser extent seasonal patterns of denitrification (as determined by water filled pore space in the upper horizons) may also influence nitrate leaching, particularly in soils with slower permeability and lower porosities. This variable could be accounted for more fully through a daily soil water balance.

5.3 Alternative approaches for rating nitrate leaching potential

We have undertaken a review of alternatives (separate report available on request), according to tiers of model complexity that are roughly analogous to tiers used in the IPCC guidelines to differentiate method complexities for calculating greenhouse gas inventories. The soil nitrate leaching vulnerability index used in this report qualifies as a Tier 1a model:

- Tier-1a refers to index models or indicators that are largely based on empirical relationships, weighting factors, and readily available data. They are simple models with minimal data requirements that can be operated quickly. Accuracies can be variable, but with some examples a simple model can provide a more than adequate answer depending on modelling purpose.
- Tier-1b are similar but with slightly more complexity, such as management components and nitrogen transformations.
- Tier-2 models are more complex, involving strong empirical relationships or modelled processes, or a combination of both (e.g. Overseer®). A key characteristic is the estimation of actual N-leaching losses, and the capability of scenario modelling (e.g. for evaluating mitigations). Tier-2 models are often regarded as a compromise between process representation, depth of parameterisation, ease of use, availability of data, and speed of operation.
- Tier-3 is the most complex level, usually referring to detailed research models with extensive supportive field study research. NZ examples include APSIM and SPASMO.

Tier-3 models tend to be the most robust but have a high data and parameterisation requirement, and expert user knowledge is required.

Many alternative Tier 1 models have been developed for other countries, but they would require adaptation, development, and testing for NZ's unique soil/climate/land use combinations (comparable types of pastoral farming are not that common in a global sense). We do not, therefore, recommend any Tier 1 alternatives, given that the N-leaching vulnerability index is already available.

It is also relevant to note that Landcare Research is unlikely to shift beyond a Tier 1 approach for calculating N-leaching vulnerability in an S-map context (at least in the short term). As it stands, the index achieves a fair level of performance and it has the particular quality of being quick to calculate. This is a fundamental requirement as S-map coverage is constantly expanding and new soils are being added. However, as identified in Section 5.2.3, there is scope for possible improvement by adding bypass flow, improved den trification, and deep drainage estimates (all of which require further evaluation), as well as potential improvements through the development of a spatial soil water balance that would shift the index to at least a Tier 1b model.

Literature regarding applicable Tier 2 models that include pastoral farming systems is sparse. Indeed, it is a common lament of overseas pastoral-orientated commentators that they do not have a tool like Overseer®. We therefore limit our discussion to the potential of this particular model, given that it has already been developed and validated for NZ conditions, and that Overseer® estimates are widely accepted in NZ. However, in its most accessible form, Overseer® is an aspatial model where the spatial component is dealt with on an implicit level (e.g. users specify blocks, but there is no spatially explicit representation of blocks). Two options are available for making Overseer® more spatial.

Dymond et al. (2013) used Overseer® to produce a national map of nitrate-leaching by modelling a limited number of representative farms and extrapolating the results by AgriBase stocking rate. A similar approach could be adapted whereby environmental factors are used to extrapolate model results from reference farms. However, the technique of Dymond et al. (2013) has already been superseded, and it is now possible to run Overseer® for large numbers of farms.

Pollacco et al. (2014) ran the Overseer® DLL (dynamic linked library) in a batch mode, which quickly allowed them to evaluate the implications of changing soil parameters for two farm systems (cropping and dairy). In doing so, they were able to model all S-map soils through Overseer®, effectively representing 4470 individual instances of Overseer® modelling. A similar batch interface has been developed by Rezare Systems for Environment Canterbury, who used the batch processer to generate nitrate-leaching estimates used in the development of the Matrix of Good Management (MGM). A high number of input variables can be adjusted with the MGM batch processor. Both require a special license to use the underlying Overseer® model, available by making a submission to the Overseer® owners.

A Tier 2 estimate of nitrate-leaching potential is possible by designing reference farm systems (e.g. sheep/beef, dairy, cropping), and then batch process them through Overseer® for every soil-climate combination or for every farm unit. Results can then be analysed statistically into leaching potential classes. An added level of sophistication would be creating blocks similar to the method of Manderson (2015a), who used GIS data to create and parameterise blocks for Overseer® base modelling of 123 farms in the Mangatainoka catchment.

This option is achievable, likely to have a relatively low cost, and would achieve a level of rigour that will be accepted by many NZ interests. Further, it would be a valid dataset for making comparisons (as the results of Pollacco et al. 2014 have been used in this report). However, Overseer® may not have the confidence of all scientists, especially in an international context.

A high level of science rigour is perhaps best achieved by shifting to a Tier 3 model. In this case we limit our discussion to SPASMO and APSIM, both of which can be described as the prevailing process models currently used in NZ for agricultural nutrient-loss assessment. SPASMO has been successfully used to provide spatial estimates of nitrate-leaching (e.g. Green & Manderson 2012), but it is proprietary software that can only be used under contract to Plant and Food Research.

In contrast, APSIM is open source software with a particularly strong pasture module (AgPasture originally from EcoMod). APSIM is similar to SPASMO, but has a far higher international user-base with a high volume of science publications. Added advantages are that APSIM is officially the preferred process model for NZ Crown Research Institutes, and that it is currently being developed for spatial applications as part of a Landcare led research project. Part of this project involves the automatic translation of all S-map soils into APSIM parameter files; limited soil data have always been a bottleneck for the use of all process models in a spatial framework.

In summary, we do not advocate further consideration of alternative Tier 1 models, as the N-leaching vulnerability index has already been developed for NZ conditions, and already achieves a fair level of performance. Shifting to a Tier 2 model is possible by obtaining a license to run the MGM batch processer. This could be applied to a small number of reference farm designs, across all soil-climate combinations. Tier 3 offers the highest level of science rigour. If this path is of interest, we would recommend the use of APSIM because of its transparency, accessibility, and its current use in existing programmes for making spatial estimates of N leaching.

6 Additional advice regarding the development of the AgIM model

6.1 Suggestions for integrating soil information into the freshwater model

From a GIS perspective, a potential option for integrating soil information into the freshwater model is to spatially disaggregate farms by soil types before AgIM modelling. However, this is likely an invalid option because there is no easy way to distribute farm livestock numbers proportionally by farm soil types, and even if we could, the resulting number of individual records would likely represent a significant processing constraint on the use of the AgIM model.

A potentially more robust option would be the stratification of the $\text{Frac}_{\text{LEACH}}$ component associated with the nitrous oxide emission pathways of the AgIM model.

6.1.1 AgIM nitrous oxide emission pathways

AgIM is a modification of the NZ Agricultural GHG Inventory calculator (Section 2), which in turn is based on IPCC guidelines and methodologies. A key feature of the IPCC methodologies is the use of emission pathways to partition GHGs losses. Of interest here are the pathways for estimating nitrous oxide emissions especially those that involve excreta return and fertiliser use as it applies to NZ agriculture (Fig. 14).

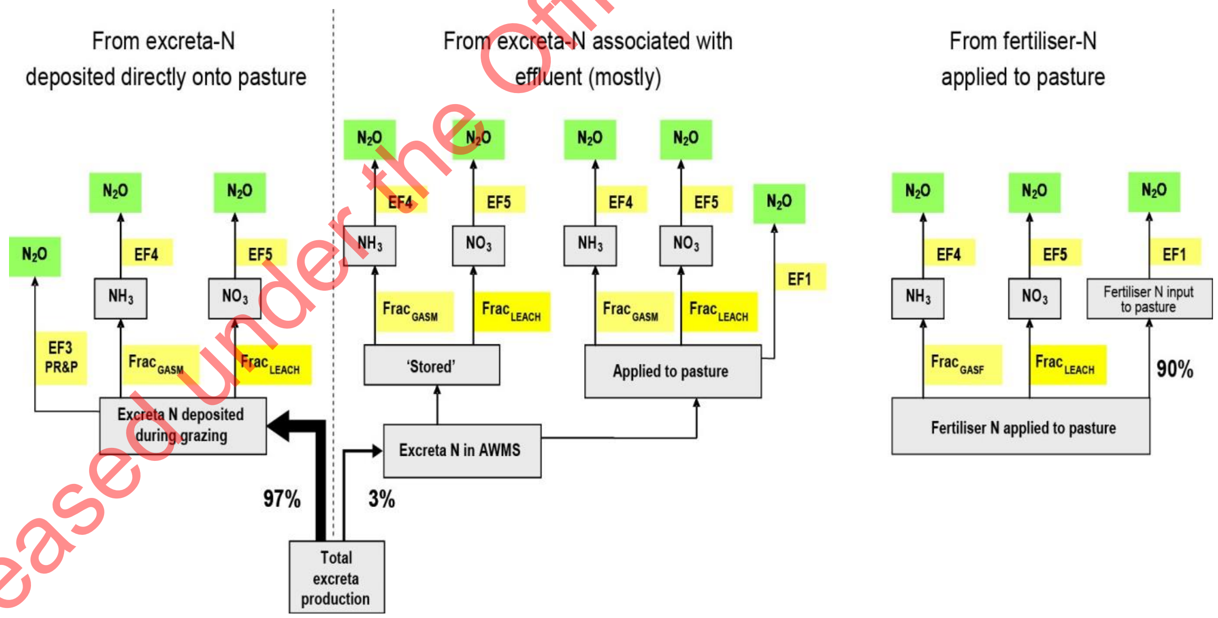

Figure 14 Emission pathways for nitrous oxide losses associated with livestock excreta and fertiliser in NZ agriculture (adapted from Sherlock et al. 2011).

Total excreta production is estimated as the difference in livestock nitrogen intake (as a percent of dry matter intake) and nitrogen lost in animal product. The result (total excreta production) is then partitioned by deposition environment, with the majority (97%) being deposited directly to pasture during grazing (for NZ livestock grazing systems), and the balance (3%) being stored or indirectly applied to pasture as effluent as part of Animal Waste Management Systems (AWMS).

Excreta-N is then partitioned as the fraction returned as livestock manure ($Frac_{GASM}$), and the fraction that is lost through leaching and run-off ($Frac_{LEACH}$). In turn, each fraction is multiplied by a specific emission factor (EF*x*) to estimate nitrous oxide losses. Fertiliser emissions are calculated directly from the amount of fertiliser-N applied to pasture, using both $Frac_{LEACH}$ and a fertiliser-specific fractionation ($Frac_{GASF}$).

6.1.2 $Frac_{LEACH}$

For IPCC Tier 1 methodologies, a universal default value of 0.3 is suggested for $Frac_{LEACH}$, with an acknowledged potential range of 0.1 – 0.8 (IPCC 2000). These values are based on the general knowledge of an expert group and a global-scale modelling study of N-loading in rivers (Nevison 2000), and are thus intended to be broad and all-encompassing. Countries are, therefore, encouraged to develop their own country-specific $Frac_{LEACH}$ values using measured N-leach and runoff values if available. Several have already developed their own values from country-specific research findings, and at least twelve countries have adopted $Frac_{LEACH}$ values that are lower than the IPCC default (Eder et al. 2015).

New Zealand initially adopted a $Frac_{LEACH}$ value of 0.15. This lower value was considered more appropriate for NZ's predominantly pastoral farming systems, and was based on early studies that showed N-leaching and runoff was 15% or less of the amount of N applied (as discussed in Thomas et al. 2005).

New Zealand's $Frac_{LEACH}$ value was further refined down to 0.07 in a study that compared N-leaching estimates using both the IPCC formula and Overseer® nutrient budgets (Thomas et al. 2005). The comparison used four farming types (dairy, sheep and beef, arable, and vegetable farms) with the pastoral types further differentiated into three levels of farming intensity. Results suggested that existing $Frac_{LEACH}$ values were too high for dairy and sheep and beef farming systems, but comparable to the IPCC 0.3 default for arable and vegetable cropping. Pastoral farming occupies the greatest area by far of farmed land in NZ, so a value of 0.07 was suggested as a more representative value for NZ farming conditions. This is the value currently used in the calculation of NZ's agriculture greenhouse gas inventory.

While not part of this report's focus, it is important to note that Thomas et al. (2005) and others demonstrated that $Frac_{LEACH}$ can be stratified by land use type (i.e. pastoral and arable/cropping). Further, it is equally important to note that the manner in which Overseer estimates N-leaching has changed since this study (shift from version 5 to 6). Last, Thomas et al. (2005) used a limited range of soil-climate combinations for Overseer® modelling.

6.1.3 $\text{Frac}_{\text{LEACH}}$ stratification by leaching environments

Most countries use a single $\text{Frac}_{\text{LEACH}}$ value for national inventory calculations. In effect this represents an assumed average of N-leaching and runoff from all possible combinations of soil and climate for entire countries. However, as demonstrated in Section 2.2, the effect of soil variation alone on N-leaching is high. The effect of climate can be even higher, as climate strongly determines the amount of water that passes through the soil profile and flushes nitrogen into deep drainage.

IPCC guidelines acknowledge that different leaching environments can have different $\text{Frac}_{\text{LEACH}}$ values. According to IPCC (2006) guidelines, a $\text{Frac}_{\text{LEACH}}$ value of zero could be assumed for non-irrigated dryland regions where evapotranspiration potential exceeds precipitation most of the year (and thus, leaching is unlikely to occur). In humid regions the value can range between 0.1 and 0.8 depending on agricultural practices.

Canada provides an example of a country that has stratified $\text{Frac}_{\text{LEACH}}$ by environments (as ecodistricts) for its national inventory calculations (Environment Canada 2010). They have assumed a minimum value of 0.05 for the country's most arid regions, slightly higher than zero in recognition that even in a dry climate a small leaching risk will remain (e.g. preferential flow in cracked soils). A maximum value of 0.3 is assumed for humid climates (i.e. the default IPCC Tier 1 value).

Stratification is achieved by using a ratio of precipitation (P) over potential evapotranspiration (PE). The maximum value of 0.3 is assumed for ecodistricts where the May to October P/PE ratio is greater or equal to 1, while the minimum 0.05 value is assumed for ecodistricts with the lowest P/PE ratio (≤ 0.23). For ecodistricts in-between, a linear decrease in $\text{Frac}_{\text{LEACH}}$ is assumed (Fig. 15). The regression shown in the figure has been derived from field studies in typical climate zones and soil regions of Canadian agriculture (IPCC 2015), and only applies to P/PE ratios of 0.23 to 1.

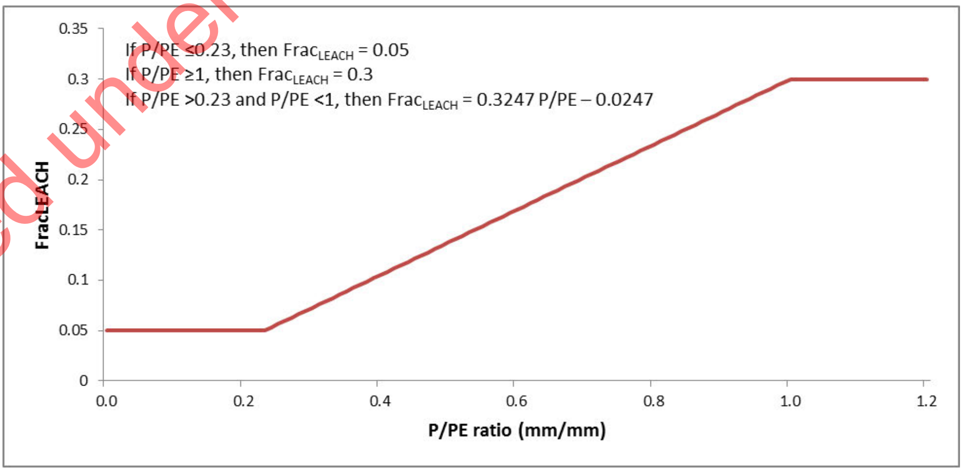

Figure 15 $\text{Frac}_{\text{LEACH}}$ stratified by ecodistricts (represented as the ratio of precipitation over potential evapotranspiration) as used in the Canadian national GHG inventory (adapted from Environment Canada 2010).

6.2 Options for developing a stratified NZ $Frac_{LEACH}$

6.2.1 Adaptation of the Canadian inventory method

The Canadian method is simple and can therefore be readily adapted for NZ conditions. Appropriate climate data are available, and measured N-leaching data can be sourced for the linear regression (e.g. see Thomas et al. (2005) for dairy farm N-leaching datasets used to validate Overseer). However, it is also a simplistic stratification, and the validity of some of assumptions is unclear:

- The P/PE ratio represents a very basic water balance, but one that does not account for the soil water-holding functionality of soils. Soil can significantly buffer the effect of climate against deep drainage and related N-leaching losses.
- The method assumes no change in $Frac_{LEACH}$ when $P \geq PE$ (i.e. $P/PE \geq 1$), which is a critical point were precipitation exceeds potential evapotranspiration, and the likelihood of leaching and runoff should actually increase.
- It is unclear if and how irrigated agriculture has been factored into the method. This may or may not be a significant practice in Canada, but in NZ irrigation it is a widespread and increasing activity.
- The method assumes a maximum $Frac_{LEACH}$ of 0.3 (the IPCC default for Tier 1 calculations). However, the IPCC default is more likely to been intended as a central tendency value (mean, median). IPCC (2006) state that a $Frac_{LEACH}$ maximum can potentially be as high as 0.8.

Adaptation for NZ conditions is still a feasible option if these considerations can be addressed and/or improved upon. In particular, we would recommend the use of either measured or robustly modelled values for the upper and lower $Frac_{LEACH}$ thresholds (i.e. they must be defensible), and the replacement of the P/PE ratio with a national soil-water balance. Generating a spatial soil water-balance for all of NZ to replace and improve on the P/PE ratio is an entirely feasible proposition (as discussed in Section 5.3).

However, neither of these improvements would accommodate the often substantial $Frac_{LEACH}$ differences that have been reported between different land use types (namely differences between pastoral systems and arable/cropping systems).

6.2.2 Replicating Thomas et al. (2005) using a wider selection of soil-climate combinations

Thomas et al. (2005) has established the use of Overseer® as a valid method for estimating $Frac_{LEACH}$ values representative of NZ farming systems. However, there are limitations to the method:

- Overseer® has changed considerably since the Thomas et al. (2005), with a full version change resulting in a shift to monthly soil water balance modelling, and the inclusion of improved arable/cropping models. If Thomas et al.'s Version 5 models were imported and rerun through Version 6, we would definitely expect a change in N-leaching levels, and possibly a change in the ratio of N-inputs to N-leaching. This also has implications for NZ's current GHG inventory calculations.

- We do not know if the Overseer® models (.ovp files) used by Thomas et al. (2005) are still available. Likewise, it is not clear if the descriptions of the farm models in the paper are sufficiently complete to allow the models to be rebuilt.
- A limited number of soil-climate combinations were used in the study. They appear to cover only a limited number of combinations, and it is arguable that they adequately cover the dominant combinations (no strong evidence is given to support their selection).
- The greatest limitation, however, is a reliance on the principle of 'representative' or 'typical' farm systems, whereby a small number of farm models are used to represent a large number of farms within a given category. This is a common use of Overseer® for making/extrapolating estimates across large areas, but it is also a grand assumption that one farm system can represent the individuality and complexities of many farms. It is also a highly subjective approach, often relying on expert judgement to identify and define representative farms. It is therefore difficult, if not impossible, to validate the representativeness of farms in a statistical sense (we don't have the data).

The limitations of a 'representative farm' approach to modelling are recognised and investigations to develop more robust methods are currently being developed. For example, Manderson (2015a) used and compared several approaches for estimating N-leaching from a large number of farms in a catchment. Lilburne et al. (2015) used a statistical clustering to categorise Canterbury into several N-leaching climate environments. This was part of the Matrix for Good Management (MGM) project that is currently generating a relatively large set of base Overseer files that represent the range of farming systems in Canterbury.

Based on these developments, we believe that replicating the Thomas et al. (2005) method with technical improvements and distributed modelling could be used to develop a stratified $Frac_{LEACH}$ system suitable for NZ farming systems and environments. Particular improvements include

- greater rigour regarding the identification and definition of representative farms. This could be achieved through an analysis of Agriculture Production Survey data. Alternatively, commercially and publically available farming datasets could be used.
- an analysis, similar to that of Lilburne et al. (2015), to identify soil-climate clusters that group similar N-leaching environments.
- Overseer® batch modelling of many potential representative farm systems. Previous studies have been limited by the number of farms that can realistically be modelled through Overseer within the timeframe of a given project. This is no longer a constraint with the new availability of batch Overseer® processing.

6.2.3 Reference farm systems option

This is a partly tested option that is only made possible with the advent of Overseer® batch processing. It involves modelling one farm system (the reference farm) across all soil-climate combinations in NZ. Land use and management variables are held constant, with soil and climate being the only variables that are changed. This allows for a more valid comparison of N-leaching potential between different soil-climate combinations.

A key component is to develop a clear and transparent definition of the reference farm to be modelled. This is based on the concept of *reference crop evaporation*, which is used to estimate a value according to a tightly defined set of reference conditions, i.e. *evapotranspiration rate of a short green crop (grass), completely shading the ground, of uniform height and with adequate water status in the soil profile*.

Using one reference farm system provides simplicity, and we believe it can be used to provide a robust stratification of $\text{Frac}_{\text{LEACH}}$ for a single set of specified conditions. However, because great diversity exists within and between different farm types, it may be a challenge to identify a reference farm system that is agreeable to many parties. Likewise, $\text{Frac}_{\text{LEACH}}$ is known to vary between agricultural land-use types (e.g. Thomas et al. 2005).

A logical progression is to introduce more than one reference farm system. Lilburne et al. (2015) demonstrated the 'reference farm' method applied to soil variation using two farm systems. They implemented two Overseer® farm models (dairy and cropping under single climate conditions) across all S-map soil siblings to estimate N-leaching variation across soils. We propose to advance this technique by including the additional variable of climate (i.e. as soil-climate clusters), together with a larger number of reference farm systems. This creates two different options for representing a stratified $\text{Frac}_{\text{LEACH}}$:

- Stratification by both land use and soil-climate N-leaching environments, i.e. each land use type has its own stratified $\text{Frac}_{\text{LEACH}}$ values based on a single reference farm system (representing that land use).
- Aggregation to identify the average $\text{Frac}_{\text{LEACH}}$ value for a given soil-climate combination (i.e. the average $\text{Frac}_{\text{LEACH}}$ across all modelled reference farms).

There are operational considerations that require further investigation. For example, it is nonsensical to apply certain land use systems to certain farming environments (e.g. vegetable cropping in steep hill country). It may be possible to accommodate this through the application of land-use suitability evaluation techniques. Consideration is also required for the modelling of pastoral farm systems, especially the management of Overseer® pasture production under different soil-climate combinations.

An alternative is to use APSIM rather than Overseer®. APSIM is a more challenging model to use correctly, but the results are likely to be more transparent. Further, recent advances now allow APSIM to draw on S-map data in a quasi-spatial manner. The greatest potential advantage, however, is that APSIM allows for the construction of more abstract 'representative systems'.

6.2.4 Recommendations for the development of a stratified $Frac_{LEACH}$

We consider the stratification of $Frac_{LEACH}$ as the most suitable overall approach for integrating the effects of soil and climate on N-leaching for the AgIM model. Three main stratification options have been described:

1. Adapting the Canadian method using NZ-specific research, and improvement by developing a national soil water balance to replace the P/PE ratio. The general method is already accepted to IPCC standards, and is relatively simple to adapt. We recommend this as the safest option for developing a stratified NZ $Frac_{LEACH}$, but with the acknowledgement that it fails to capture $Frac_{LEACH}$ differences between land uses.
2. Adapting the 'representative Overseer® farms' approach of Thomas et al. (2005) but with a larger number of farms, and more rigorous determination of farm system design and soil-climate clusters. Thomas et al. (2005) has demonstrated that Overseer® is an acceptable tool for estimating NZ $Frac_{LEACH}$ values, and we now have the capacity to model many farm systems relatively quickly. We recommend this as the most suitable option for accommodating $Frac_{LEACH}$ differences related to both land use and soil-climate N-leaching potentials.
3. Developing the concept of 'reference farm systems', which provide stratified soil-climate $Frac_{LEACH}$ estimates according to a defined set of land use conditions (the reference). We recommend this as a suitable option that carries potential for purposes other than just $Frac_{LEACH}$ (e.g. has implications for equitable allocation of nutrient loss limits), but we acknowledge that this approach needs more critical thinking and development (i.e. there is more uncertainty in this option).

The development of any selected option will need to meet standards for Tier 1 statistics. Towards this end, we recommend that the chosen method is developed by a multi-disciplinary science team (cross CRI) together with MPI involvement, with a paper published in an international journal being specified as a key output.

6.3 Options for representing $Frac_{LEACH}$ by farm

The AgIM model uses farms as the smallest unit of analysis. A stratified $Frac_{LEACH}$, however, will likely be calculated from a combination of soils and climates, neither of which correspond well with the farm unit (i.e. there is often soil variation within farms, and to a lesser extent it is also possible to have climate variation within a farm depending on farm size and local climate gradients). We offer three options for dealing with this scale mismatch:

- Use the dominant $Frac_{LEACH}$ value by area, to represent the $Frac_{LEACH}$ value for the entire farm; however, this option is limited when considerably different $Frac_{LEACH}$ values occur on the same farm across large areas (e.g. 49% = 0.3 and 51% = 0.09).
- Average using the arithmetic mean (or similar measure of central tendency) all $Frac_{LEACH}$ values to produce a single farm value.

- Weighted average (weighted by area) applied to the N-leaching results before they are converted to $\mathrm{Frac}_{\mathrm{LEACH}}$ values.
- Average $\mathrm{Frac}_{\mathrm{LEACH}}$ values to the whole farm level using the geometric mean, which is generally a more suitable averaging technique when using interrelated data.
- Distribute livestock excreta within farms. In this case no aggregation of $\mathrm{Frac}_{\mathrm{LEACH}}$ would be required (see next section).

The aggregation technique most suitable for these types of data needs to be determined by an experienced statistician (i.e. the most suitable option regarding the arithmetic mean, weighted mean, and geometric mean).

6.4 Options for distributing livestock excreta within farms

The AgIM model produces whole farm outputs. For example, the mass of livestock excreta calculated by AgIM will be for an entire farm. To use the result one must assume a uniform excreta return pattern across the entire farm. In many cases, however, excreta return patterns are decidedly non-uniform. Here we consider two options for distributing AgIM livestock excreta within farms.

6.4.1 Distribution by livestock numbers

The NZLRI is a national digital inventory of land resources. Amongst other things it includes an estimate of three types of stock carrying capacity by LUC unit. These can be used to approximate potential livestock distribution patterns within farms (Fig. 16). Areas of land with a higher stock carrying capacity will grow more grass, have higher residency times for livestock grazing (i.e. higher livestock numbers), and will thus, have higher rates of excreta return.

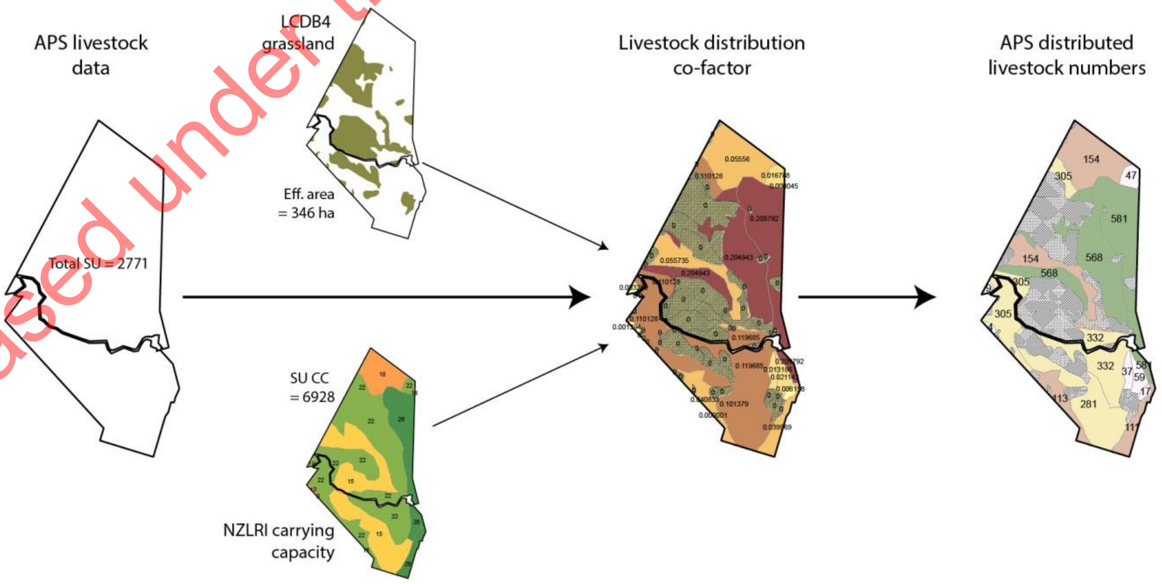

Figure 16 Method for distributing livestock numbers within a farm by carrying capacity.

NZLRI stock carrying capacities are subjectively derived (see Manderson 2015b), but reasonable relationships have been identified when compared against AgriBase livestock data. Manderson (2015a) compared NZLRI and AgriBase stock units for 243 sheep and beef farms and found a reasonably strong relationship (R2 = 0.82), while Ausseil et al. (2013) compared all AgriBase livestock numbers for sheep/beef and dairy, and achieved agreements of 0.7 and 0.4.

The validity of this method is likely to be strongest in hill country, where stocking rates are generally less intense, and where differences in production are largely related to topography (we can draw on many pasture growth trials to demonstrate this). However, where livestock intensities are high, the influence of landscape is less pronounced because of intensive farm management (e.g. soil fertility, purchased supplements, irrigation, drainage). In such cases (e.g. intensive dairy, arable, vegetable cropping) the method is unsuitable.

Accordingly, the method should be used selectively (if at all) while considering the following:

- The method can be applied as a final step of data preparation before AgIM modelling. This would involve creating a national layer of stocking distribution within farms from APS farm parcels and NZLRI carrying capacities, and then multiplying this against APS livestock numbers.
- APS data could be used to further validate the method. To date, comparisons have been based on AgriBase data with unknown levels of reliability.
- A rule is required to apply the method only to low intensity farms and hill country farms.

We can, however, conceptualise three main challenges. First, fractioning farm parcels will increase the number the entities or records to be modelled through AgIM. This may be a challenge for a spreadsheet-based model, but it would not be a limitation if AgIM was rebuilt in a spatial GIS framework.

Second, it is not clear if this method would add substantially more value than the relatively more straightforward method of distributing excreta by topography (following section).

Third and most important, this method does not distinguish between stock types, and cannot therefore be used for farms with multiple livestock enterprises. For example, deer enterprises requiring special fencing are often run as spatially separate units within sheep and beef farms. We have no spatial dataset or method to partition these types of enterprises within farms.

Based on these limitations, we would not recommend the use of this method for AgIM modelling.

6.4.2 Distribution of excreta return by topography classes

Livestock excreta return patterns in hill country are non-uniform, and tend to be higher on flatter slopes, and relatively minor on the steepest slopes (Fig. 17). Considerable investigation has been invested in identifying these relationships, and how they can be used to improve nitrous oxide emission estimates from hill country. The methods are published in international literature (Saggar et al. 2015) and are currently being considered for inclusion in NZ's GHG inventory.

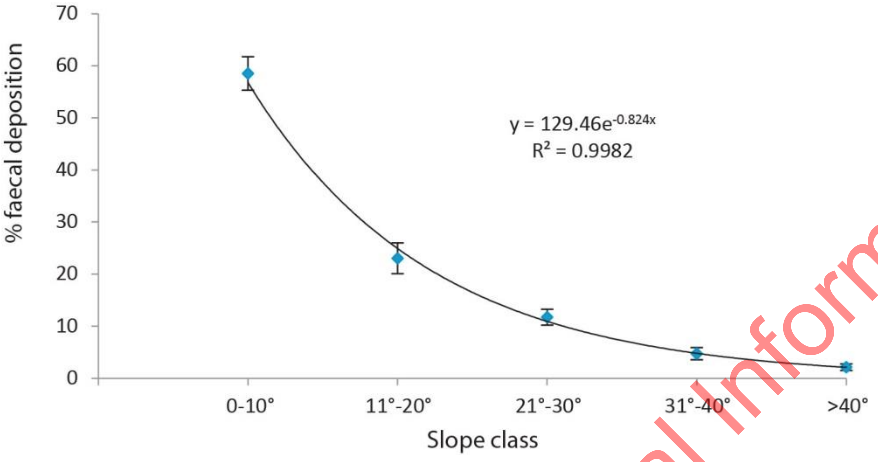

Figure 17 Relationship between average faecal deposition and slope class across five farmlets under sheep grazing (Rowarth 1987; Saggar et al. 2015).

The GHG inventory nitrous oxide calculations can use special EF_3 emission factors for different slope classes (Kelliher et al. 2014). No slope-based equivalents exist for $Frac_{LEACH}$, meaning the calculations can only be made in a GIS framework (cf. N_xO calculations that can be made in a spreadsheet).

Accordingly, we do not recommend use of the 'excreta returns by slope' relationships if $Frac_{LEACH}$ is to be aggregated as a single value for individual farms (Section 6.3). We do, however, recommend the method if $Frac_{LEACH}$ remains disaggregated for farms.

However, the calculations can be made in a GIS framework after AgIM modelling to fully utilise the actual $Frac_{LEACH}$ values (e.g. whole farm excreta estimates from AgIM are linked back to APS parcels, overlaid with slope classes to distribute excreta return within APS parcels, and then overlaid again with the $Frac_{LEACH}$ layer to estimate the fraction of N lost to leaching and runoff. Results are readily summed back to farms, catchments, etc.).

7 Conclusions

We have generated an interim hybrid national soil layer that combines the latest S-map with the FSL database. S-map represents 28% of the layer (7.5 M ha).

- The reliability of the FSLs is generally poor relative to S-map. When the two are compared at the most detailed level of the NZ Soil Classification, the FSL has a classification accuracy of 0.17 (kappa = 0.13) and a map accuracy of 0.32 (kappa = 0.30), which equates to only slight and fair levels of agreement with S-map.
- Confidence for the entire hybrid database is rated as 6% High, 12% Medium, 11% Low, and 70% Very Low (mostly for FSL data).
- FSL-based options to improve the accuracy of the hybrid layer will likely involve substantial cost, but the results will still be of lower quality relative to S-map. More effective options include integrating remaining legacy soil maps into S-map (~1 M ha), and supporting the acceleration of the S-map programme.

Nitrate leaching potential has been examined using the soil nitrate-leaching vulnerability index of Webb et al. (2010).

- The soil vulnerability index is simple and easy to implement, yet built from a sound theoretical basis according to key soil properties that exhibit strong relationships with N-leaching. When compared against Overseer® modelled N-leaching it achieves a reasonably strong relationship except at the Very Low vulnerability class.
- The vulnerability of NZ soils to nitrate leaching loss is rated as Very Low (5% of NZ soils), Low (25%), Moderate (19%), High (23%), and Very High (18%).
- The accuracy of FSL vulnerability ratings is generally poor relative to S-map. A classification accuracy of 0.32 (kappa = 0.12) indicates only slight agreement, and a map accuracy of 0.42 (kappa = 0.25) indicates fair agreement. Confidence for the FSL N-leaching vulnerability component of the hybrid layer is Low to Very Low.

Landcare Research is satisfied with the performance of the N-leaching vulnerability index, and will continue to update it for S-map purposes. However, we have considered several options that could provide an improved or alternative system of representing N-leaching potential across NZ:

- Improving the vulnerability index through the integration of bypass flow, improved estimates of denitrification, and deep drainage losses. Deep drainage and denitrification could be better accounted for using spatial daily water balances.
- Implement Overseer® across all NZ soils using 'reference farm systems'. Relative N-leaching from soils under the same farm system can then be classified into a classification of N-leaching potential.
- As above, but use the APSIM model to generate N-leaching estimates for 'soil-climate-reference farm system' combinations across NZ. Validity of this option is vastly improved by recent automatic translation of S-map soil properties into APSIM equivalents.

A national layer of nitrate leaching potential does not immediately translate into a 'ready to use' option for the MfE freshwater model. For this, the most suitable overall approach would involve the stratification of the $Frac_{LEACH}$ component of the AgIM model (currently uses a single $Frac_{LEACH}$ value for all of NZ). We have identified three options:

1. Adaptation of the Canadian system of stratifying $Frac_{LEACH}$ using NZ-specific research and a national soil water balance.

2. Improvement of the 'representative Overseer® farms' method, originally used to develop NZ's current single $Frac_{LEACH}$ value. Improvements include a larger number of representative farms, and more rigorous determination of farm system design and soil-climate clusters (using the 'nitrate leaching potential' layer from this project).

3. Development of the 'reference farm system' approach, which uses a defined set of conditions (the reference) to generate a set of reference values (e.g. reference N-leaching).

8 Recommendations

- That MfE use the national hybrid soil map in the freshwater model, while recognising it is an interim dataset and the FSL component (72%) has low accuracy and Low to Very Low confidence.
- Invest in the development of a stratified $Frac_{LEACH}$ for NZ. All three options described in this report are valid, but differ in terms of risk and rigour:
    1. An adapted Canadian method is recommended as a simple and safe option. The general method is already accepted by the IPCC (i.e. achieves their standard). However, the method does not capture differences between land uses.
    2. The 'representative Overseer® farms' method is recommended as the most robust option for accommodating $Frac_{LEACH}$ differences related to both land use and soil-climate N-leaching potentials.
    3. The 'reference farm system' is recommended as a suitable option with high potential (including for purposes other than stratifying $Frac_{LEACH}$), but is the least developed option (i.e. this option has the greatest uncertainty).
- Any development of a stratified NZ $Frac_{LEACH}$ will need to achieve Tier 1 statistics standards. For this we recommend a multi-disciplinary development team including MPI, and a published journal paper specified as a key output.
- There will be a scale-mismatch between APS data (farm units) and stratified $Frac_{LEACH}$ values (soil-climate units). We have made suggestions on how this can be managed, but further consideration is required.
- Rebuild the AgIM model in a spatial modelling framework. With the existing design there will be considerable (inefficient) crossover between GIS and the AgIM spreadsheet, and a spatial AgIM would resolve scale-mismatch issues and allow for rapid testing of any GHG inventory or AgIM downscaling proposals.

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