Land Use in Rural New Zealand: Spatial Land-use, Land-use Change, and Model Validation

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Abstract
Land is an important social and economic resource. Knowing the spatial distribution of land use and the expected location of future land-use change is important to inform decision makers. This paper documents and validates the baseline land-use maps and the algorithm for spatial land-use change incorporated in the Land Use in Rural New Zealand model (LURNZ). At the time of writing, LURNZ is the only national-level land-use model of New Zealand. While developed for New Zealand, the model provides an intuitive algorithm that would be straightforward to apply to different locations and at different spatial resolutions. LURNZ is based on a heuristic model of dynamic land-use optimisation with conversion costs. It allocates land-use changes to each pixel using a combination of pixel probabilities in a deterministic algorithm and calibration to national-level changes. We simulate out of sample and compare to observed data. As a result of the model construction, we underestimate the "churn" in land use. We demonstrate that the algorithm assigns changes in land use to pixels that are similar in quality to the pixels where land-use changes are observed to occur. We also show that there is a strong positive relationship between observed territorial-authority-level dairy changes and simulated changes in dairy area.

JEL codes
R52; R13; Q15; C52

Keywords
Agriculture, land use, LURNZ, maps, rural, spatial, land-use model, model validation

Contents

1. Introduction

The growing global population is placing ever-increasing pressure on one of our most important social and economic resources – land. Knowing the spatial distribution of land use and the likely location of land-use change under different future scenarios is important for informed public and private decision making. For example: understanding the likely effects of policies to mitigate greenhouse gas emissions or policies to resolve issues of water quality and availability; planning the location and capacity of ports, processing facilities, electricity, and transport infrastructure; and predicting and preparing for the likely impacts of climate change, including vulnerability to extreme weather events, pest control, and food security.

This paper documents and validates the baseline land-use maps and the algorithm for spatial land-use change incorporated in the Land Use in Rural New Zealand model (LURNZ). Motu Economic and Public Policy Research has developed LURNZ as a national-level model of land use and land-use change.[1] This work builds on and extends earlier work by Motu described by Hendy *et al.* (2007). At the time of writing, LURNZ is the only national-level land-use model of New Zealand (Anastasiadis *et al.* 2013). While developed for New Zealand, the model provides an intuitive algorithm that would be straightforward to apply to different locations and at different spatial resolutions.

LURNZ is based on a heuristic model of dynamic land-use optimisation with conversion costs. It allocates nationally projected land-use changes to each pixel using a combination of pixel probabilities in a deterministic algorithm and calibration to national-level changes. We simulate a land use map for 2008 and compare to observed data. We find that the model does much better than random assignment when allocating changes in each land use as measured by two key characteristics of the land where change occurs: slope and stock-carrying capacity. We find that the model generally locates dairy expansion in the regions where it actually occurs but does not match the scale of actual changes. As a result of the model construction, we underestimate the "churn" in land use.

The use and application of spatially explicit land-use models has become more prevalent with the availability of remote-sensor data, such as satellite images and aerial photographs (Heistermann *et al.* 2006). Spatially explicit models that simulate or project land-use change can be broadly classified by their geographic and temporal scale, and the resolution at which land-use

[1] For code, other documentation, and access to data for research purposes, go to http://www.motu.org.nz/research/group/land_use_in_rural_new_zealand_model

decisions are modelled. For a summary of land-use models in New Zealand, see Anastasiadis *et al.* (2013).

There are three basic types of land-use models, which differ in scale and complexity: Aggregate Systems Models (ASMs), Cellular Automata Models (CAMs), and Agent Based Models (ABMs). The three types of models differ in their construction and are useful for addressing different questions.

ASMs can be used to simulate land-use change scenarios at the national or regional scale. The most common types of ASMs are statistical/econometric models, or Computable General Equilibrium (CGE) models. These models express national/regional land-use patterns as a function of key inputs into the land-use decisions (for example, commodity prices). Statistical or econometric models use historic data to estimate the relationship between land use and the variables of interest; parameters in CGE models are chosen to be consistent with estimates from other relevant studies. Some parameters may then be adjusted such that the model provides a reasonable approximation to the historic data, and the sensitivity of the model to changes in parameter values can be tested. The first module of LURNZ can be described as an econometric ASM, where national-level land-use shares are determined by commodity prices and interest rates. These types of models are most useful for examining large-scale issues where system interactions are important. Hertel *et al.* (2009) provide an overview of how land use has been incorporated into CGE models.

CAMs model land-use change at the level of individual land pixels. Lubowski *et al.* (2006) developed one example of a CAM. The authors econometrically estimate the probability of a land parcel transitioning land use as a function of the economic returns of the initial and possible future land uses. They then use their model to simulate land-use change under various policy scenarios incentivising forestry carbon sequestration. The Lubowski *et al.* (2006) model has been applied by other researchers to simulate land use under a variety of scenarios, including agricultural subsidies and increases in urban rents (see, for example, Hamilton *et al.* (2013); Martinuzzi *et al.* (2014); Radeloff *et al.* (2012)). CAMs for New Zealand include the New Zealand Forest and Agricultural Regional Model (NZ-FARM) (Daigneault *et al.* 2011) and the NManager model (Anastasiadis *et al.* 2011). The land-use decisions in these models are based on a simple optimisation problem. CAMs can also allow spatial interaction among pixels. CAMs are useful for simulating individual agent/pixel responses and for examining issues where partial equilibrium provides a good approximation.

The second module of LURNZ could be classified as a combination of an ASM and a CAM. Land use is modelled at the level of individual land pixels, but the total land-use changes across all pixels are constrained to be consistent with scenario-specific or econometrically projected changes in national land-use areas. Land-use changes on each pixel hence depend not only on that pixel's characteristics but also on the entire distribution of pixel characteristics.

ABMs explicitly model the human decision-making process. These models allow for a wide range of behavioural phenomena and social interactions. In ABMs, the utility functions of the agents are included explicitly. This means that ABMs are more useful for questions involving non-optimising behaviour or for modelling complex interactions among agents. An example of a generalised ABM is the Mr. Potatohead model of Parker *et al.* (2008). This model was extended by Filatova *et al.* (2009) to simulate a hypothetical coastal city. In this model, agents are assumed to benefit from clustering, but suffer a risk of flooding by locating too close to the sea. This model was parameterised by econometrically estimating land-rent functions. An example of an ABM to simulate land use in New Zealand is the Agent Based Rural Land Use New Zealand model (ARLUNZ) (Daigneault and Morgan 2012).

For all models, choices must be made, which affect the model's complexity, transparency, data requirements and computational speed. More complex models enable a greater range of dynamics, heterogeneity and feedback loops, but may require more detailed data and generally require more processing time. More transparent models make it easier to develop intuition about the causes and robustness of results and to communicate the model to external users. LURNZ has been developed with an emphasis on transparency, so that it is straightforward for modellers, non-modellers, and new users to understand what factors are driving the model results, and how sensitive these results are to the underlying assumptions. LURNZ operates at either a 25-hectare or 1-hectare spatial resolution. The run times are short: It takes approximately 10 minutes for the 25-hectare resolution program and two hours for the 1-hectare resolution program.

The remainder of this paper is set out as follows: Section 2 documents the construction of the baseline land-use maps used in LURNZ; Section 3 describes the algorithm for spatially allocating land-use change; and Section 4 demonstrates its validity. We conclude in Section 5.

2. The Development of Land-Use Maps for 2002 and 2008

In this section we describe the construction of national maps of land use for New Zealand. We combine maps of land cover, use, quality, and ownership, together with trends in land-use areas in two stages. First, we specify a classification for land use and construct a 2002 map consistent with this classification. Second, we construct a 2008 map of land use by combining observed land cover in 2008 with simulated changes in pastoral land use from 2002.

We construct maps for the years 2002 and 2008 as these are the most recent years for which spatial land-cover (observed in both 2002 and 2008) and land-use (observed in 2002 only) data are available for the whole of New Zealand. The resulting 2008 land-use map is a key input for the LURNZ model, when simulating land use from 2009 onwards. Table 1 shows the land-use classes chosen in response to New Zealand needs and data.

Table 1: Land-use classes and codes for constructed land-use maps

Numeric code	**Land-use class**
1	Dairy farming
2	Sheep/beef farming
3	Plantation forestry
4	Scrub land
5	Horticulture
6	Non-productive land
7	Urban area and road infrastructure
8	Other animals and lifestyle properties
9	Indigenous forest
10	Pasture on public land
11	DoC and public land (excluding pasture)

As land-use decisions on private and public land are likely to be made differently,[2] and because the focus of LURNZ is on private choices on private rural land, we differentiate between public and private land.

2.1. Data

Our data include two panel datasets and seven maps of New Zealand (land use, ownership, two maps of land cover, and three maps of land quality). All seven maps are converted from polygon maps to raster maps using ArcGIS version 10. Raster maps are constructed from a grid

[2] The South Island high country pastoral leases are an example of pasture on public land. For this land, the lease agreement controls how it may be used. This land is typically used for sheep/beef farming, with the usage unlikely to change while it remains under a pastoral lease agreement (Ann Brower, Lincoln University, pers. comm.).

of pixels, each of which takes the value at the centroid. For ease of comparison, all raster maps use the same grid.

The standard model is at a 25-hectare resolution (1 pixel = 25 hectares = 500 × 500m), which trades off detail and computing demands (finer resolutions require more computer memory and processing time). This resolution was chosen because it was judged to reflect the quality of some of the underlying datasets and it reduces the risk of spurious precision. However, the same methodology can be applied regardless of the choice of spatial scale. For example, LURNZ has also been run at a 1-hectare resolution (1 pixel = 1 hectare = 100 × 100m) for water quality in small catchments where processes occur on a small scale.

2.1.1. The Land Cover Database

The Land Cover Database, version 3 (LCDB3) provides maps of land cover for 2002 and 2008 (Landcare Research 2012). It is derived from Landsat 7 ETM and SPOT 5 satellite imagery collected at 30-meter pixels and classified into 33 different classes (see Table 12 in Appendix 2). The accuracy of the LCDB3 maps is reinforced by an intensive program of field checking. This program also gathers training data to improve satellite image interpretation (New Zealand Climate Change Office 2004).

As LCDB3 provides maps of land cover, as opposed to land use, it does not enable us to distinguish between land uses with the same land cover. In particular, we cannot distinguish pasture used for dairy farming from pasture used for sheep/beef farming, nor can we distinguish seasonal pasture from abandoned pasture in areas where scrub regeneration is slow or does not occur (for example, tussock land).

Given the LURNZ land-use classes in Table 1, we reclassify the LCDB3. Table 2 defines the reclassification for the LCDB3 maps. As we are unable to differentiate between dairy farming, sheep/beef farming, and other animals and lifestyle properties using land cover, we initially combine these land uses in a single class: pasture.

Table 2: Classifying LCDB3 land cover into the land-use classes

Land-use class	LCDB3 land-cover class		
Pasture (dairy, sheep/beef, other animals and lifestyle properties)	Depleted tussock grassland	High producing exotic grassland	Low producing grassland
	Tall tussock grassland		
Plantation forestry	Exotic forest	Forest – harvested	Deciduous hardwoods

Scrub land	Fernland	Flaxland	Gorse and/or Broom
	Broadleaved indigenous hardwoods	Manuka and/or Kanuka	Matagouri or Grey Scrub
	Mixed exotic scrubland	Sub-alpine scrubland	
Horticulture	Short-rotation cropland	Orchard, vineyard and other perennial crops	
Non-productive land	Gravel and rock	Sand and gravel	Landslide
	Surface mine and dumps	Herbaceous freshwater vegetation	Herbaceous saline vegetation
	Lake and pond	River	Mangrove
	Permanent snow and ice	Estuarine open water	Alpine grass-/herbfield
Urban area	Built-up area	Urban parkland / open space	Transport infrastructure
Indigenous forest	Indigenous forest		

The total number of hectares of land in each class, according to LCDB3, is given in Table 3. Half of the land area in New Zealand is classified as pasture.

Table 3: Area in each land-use class according to LCDB3

Land-use class according to LCDB3	Area in 2002 map ('000s ha)	Area in 2008 map ('1000s ha)
Pasture	13,059	13,211
Plantation forestry	2,067	2,115
Scrub land	2,623	2,608
Horticulture	440	471
Non-productive land	1,853	1,633
Urban	212	223
Indigenous forest	6,383	6,378
Total	26,638	26,638

2.1.2. The AgriBase Enhanced Land Cover Database

The AgriBase Enhanced Land Cover Database (ELCDB2) provides a map of land use in 2002 (AsureQuality 2008). It is constructed by AsureQuality Limited, who reclassify the pastoral and horticultural land covers from the Land Cover Database, version 2 (LCDB2) (Ministry for the Environment and Terralink International 2005) according to a 2001 snapshot of the AgriBase database (see Table 13 in Appendix 2 for a complete list of classes).

AgriBase is a geographic database that includes property locations, size, operations, and animal numbers. AgriBase was initially developed to respond to biosecurity threats, but has also been used for food safety, civil defence, and land-use analysis (AsureQuality 2010). Data are collected for administrative reasons and are updated at different times, so the database is neither a stratified sample nor a census. Although AgriBase is kept largely up to date, the ELCDB2 for 2002 is the only (almost) complete national land-use map constructed using the AgriBase data to date.

AgriBase provides further classification only for the subset of land under pastoral or horticultural use according to LCDB2. A trivial amount of land that is neither pasture nor horticulture (around 0.02 percent) is also classified by ELCDB2. The remaining land, including some pastoral land, is left unclassified by ELCDB2.

Table 4 defines the reclassification of the ELCDB2 map. ELCDB2 provides only classes for the pastoral and horticultural land covers from LCDB2. Therefore, it does not provide a classification for the entire country.

Table 4: Classifying ELCDB2 land use into land-use classes

Land-use class	ELCDB2 land-use class		
Dairy	Dairy milk production	Dairy dry stock rearing	Grazing other people's stock[3]
Sheep/beef	Beef cattle farming	Sheep farming	Mixed sheep and beef farming
Plantation forestry	Forestry		
Scrub land	Native forest blocks	Not farmed – idle	Unspecified
Horticulture	Arable cropping	Avocados	Berryfruit production
	Citrus	Cut flower growing	Orchards of unspecified type

[3] Grazing animals off the owning farm is a more common practice among dairy farms than among sheep/beef farms. Hence we classify grazing other people's stock as dairy.

	Hay fodder production	Herbs	Kiwifruit orchards
	Maize growing	Plant nursery	Nut trees
	Other fruits e.g. Cherimoyas	Other land use e.g. quarries	Other plant types e.g. Meadowfoam
	Pipfruit	Seed crops e.g. clover, Lucerne	Squash
	Stonefruit	Vegetables/market gardening	Viticulture
Other animals	Honey production/ processing	Horses (equine)	Deer farming
	Miscellaneous animal types	Kennels/catteries	Ostrich farming
	Emu	Piggeries	Aquaculture/fish hatcheries
	Poultry or egg layers	Goat farming	Zoological gardens
Lifestyle properties	Lifestyle blocks	Tourism e.g. homestays	

The total number of hectares of land in each class, according to ELCDB2, is given in Table 5. In 2002, around 12 percent of pasture land is used for dairy farming; the vast majority is sheep/beef farming.

Table 5: Area in each land-use class in 2002 according to ELCDB2 and LCDB3

Land-use class according to ELCDB2	2002 Pasture area in LCDB3 ('000s ha)	2002 Horticulture area in LCDB3 ('000s ha)	Total area in ELCDB2 ('000s ha)
Dairy	1,611	15	1,627
Sheep/beef	8,014	111	8,125
Plantation forestry	78	1	79
Scrub land	293	7	300
Horticulture	41	208	249
Other animal farming	341	10	351
Lifestyle properties	51	2	53
Unclassified	2,629	86	2,716
Total area in LCDB3	13,059	440	13,499

Some of the land classified as pastoral or horticultural land in 2002 by LCDB3 is classified as plantation forestry or scrub land by ELCDB2. Where these two maps differ we consider ELCDB2 to be the more reliable.

Some land identified as pasture or horticultural land in 2002 by LCDB3 is not classified by ELCDB2. Figure 12 in the Appendix 2 gives an example of unknown pasture around Lake Rotorua. Inspection of this land using satellite images from Google maps, investigation of its average carrying capacity, and Territorial Authority (TA)-level land-use areas suggest that this pasture is more likely to be sheep/beef farming than any other land use. We classify this land separately in Table 5, but combine it with the land classified as sheep/beef when constructing the 2002 map (see Table 6).

2.1.3. Land Ownership Map

The land ownership map created by Landcare Research (2008) identifies land under public ownership as well as privately owned land that may have some use restrictions in 2002 (such as some types of Maori land and private reserves). It is derived from the intersection of cadastral boundaries from the Corax Mobile data layer with maps of land held by Maori, and with maps of land managed by other Crown institutions (most significantly the Department of Conservation (DoC)).[4]

We differentiate between private and public land. For our purposes, private land with similar use restrictions to public land (such as private reserves) is treated as public land. Maori freehold land is treated as private land. The classification of land into public and private, along with a complete list of land-ownership classes, is given in Table 14 in the appendix.

2.1.4. Land Quality Maps

Three maps of land quality were used to support our decision making during the construction of the 2002 and 2008 land-use maps. These maps describe the average carrying capacity, the land-use capability class, and the slope for all pixels across the country.

The Average Carrying Capacity (CCAV) map provides estimates of the average stocking rate (number of stock units per hectare) that land can sustainably support (Landcare Research 2002).[5] Although the data underlying the CCAV map was constructed in the 1970s and has not

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[4] Maori freehold land is treated as private land in LURNZ. Whether a particular land pixel is under Maori freehold management affects the probability of the land being in each land use. See Timar (2011) for more details.

[5] Land that we can identify as non-productive from LCDB3 has CCAV values of zero. We assume that all land areas with CCAV values of zero are not suitable for agricultural production.

been updated to account for improvements in farming techniques or practices, we assume the map still provides a nationally consistent indicator of the relative suitability of land for agriculture.[6] Timar and Kerr (2014) show that there is a strong positive relationship between the TA-level average carrying capacity for sheep/beef and dairy land and the number of sheep, beef cattle and dairy cattle in the TA.

The Land-Use Capability (LUC) map classifies land into eight classes based on its limitations for long-term productive use (Landcare Research and Ministry of Agriculture and Forestry 2002). A range of factors is used to determine the LUC class of any given piece of land. These include underlying bedrock, soil type, slope, vegetation cover, and climate.

The slope map is part of the Land Environments of New Zealand (Landcare Research 2004). It was created using a 25-metre digital elevation model, with contour data from New Zealand's NZMS260 map series and over 2,500 independent geographic positioning system (GPS) data points (Leathwick *et al.* 2002).

2.1.5. Land Use by Territorial Authority

Agricultural land areas for each TA are available from Statistics New Zealand (SNZ). These are drawn from the Agriculture Production Censuses for 2002 and 2007, and from the Agriculture Production Surveys for 2003 to 2006 and 2008 (Statistics New Zealand 2009). However, as with the land-cover maps, the SNZ data reports pasture areas but not how the area is divided between different pastoral activities.[7]

Land areas for dairy farming for each TA in each year are available from the New Zealand Dairy Statistics reports, produced by the Livestock Improvement Corporation (LIC) and Dairy New Zealand (DairyNZ) (Livestock Improvement Corporation and Dairy New Zealand 2009). We used the reports from 2002 to 2008 to complement the pastoral land areas produced by SNZ. An overview of the trends in dairy areas is given in Figure 11 in Appendix 2.

The dairy farming areas reported by LIC and DairyNZ are census measures. These are drawn from self-reported data from farmers collected via the dairy companies (Fonterra, Westland, Tatua, Open Country) for every farm that supplies milk, and combined with data from the LIC

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[6] This assumption holds if improvements in farming techniques and practices have affected the productivity of all land proportionally.

[7] Communications with Statistics New Zealand suggest that there are significant limitations to the land-area variable reported by the Agricultural Production Censuses and Surveys: Neither the censuses nor the surveys are designed to estimate land area; the calibration and weighting of the surveys does not control for area; and definitional issues hinder accurate collection of this variable (Danny Oberhaus, Statistics New Zealand, pers. comm). As a result, we use this data only to demonstrate that our maps are broadly consistent with official national statistics, and as part of estimating annual land-use change for our validation.

national database (Glenn Hansson, LIC, pers. comm).[8] As a result, we are confident that these data provide an accurate account of the land-area used for dairy farming. We use the LIC and DairyNZ data within our maps as part of estimating changes in land use between years.

2.2. Construction of the 2002 Land-Use Map

Given the classification of land uses above, we construct a map of land use in 2002. Public land is identified according to the public ownership map. Land that is public and classified as pasture in 2002 according to LCDB3 is assigned to the "pasture on public land" land use. Land that is public and not classified as pasture in 2002 according to LCDB3 is assigned to the "DoC and public land (excluding pasture)" land use.

All land not identified as public land is assumed to be private land and is assigned to the remaining nine land uses. We combine the LCDB3 map for 2002 and the ELCDB2 map as given in Table 6 to classify the private land. For example, there are two ways land may be classified as plantation forestry in the 2002 map: Either the land is classified as plantation forestry from LCDB3, or the land is classified as pasture or horticulture from LCDB3 and as plantation forestry from ELCDB2.

Table 6: Combining LCDB3 and ELCDB2 land uses to a 2002 map

2002 land use map	Class from LCDB3	Class from ELCDB2
Dairy	Pasture or horticulture	Dairy
Sheep/beef	Pasture or horticulture	Sheep/beef
	Pasture or horticulture	Unclassified
Plantation forestry	Plantation forestry	
	Pasture or horticulture	Plantation forestry
Scrub land	Scrub land	
	Pasture or horticulture	Scrub land
Horticulture	Pasture or horticulture	Horticulture
Non-productive land	Non-productive land	
Urban land	Urban land	
Other animals and lifestyle properties	Pasture or horticulture	Other animals or lifestyle properties
Indigenous forest	Indigenous forest	

[8] Specifically, the LIC national database is used to cross-check the survey data to check the reliability of the self-reported numbers. Additionally, the LIC database is used to fill in missing values from the self-reported surveys.

Inspection of these land-use classes shows that some land classified as dairy, sheep/beef, forestry, scrub, or public pasture is unsuited for agricultural activities (in general, this is tussock land). We therefore reclassify all public pasture land with a CCAV value of zero (indicating that it is not suitable for grazing animals) as DoC and public land (excluding pasture). We reclassify all dairy, sheep/beef, forestry, and scrub land with a CCAV value of zero as non-productive land.

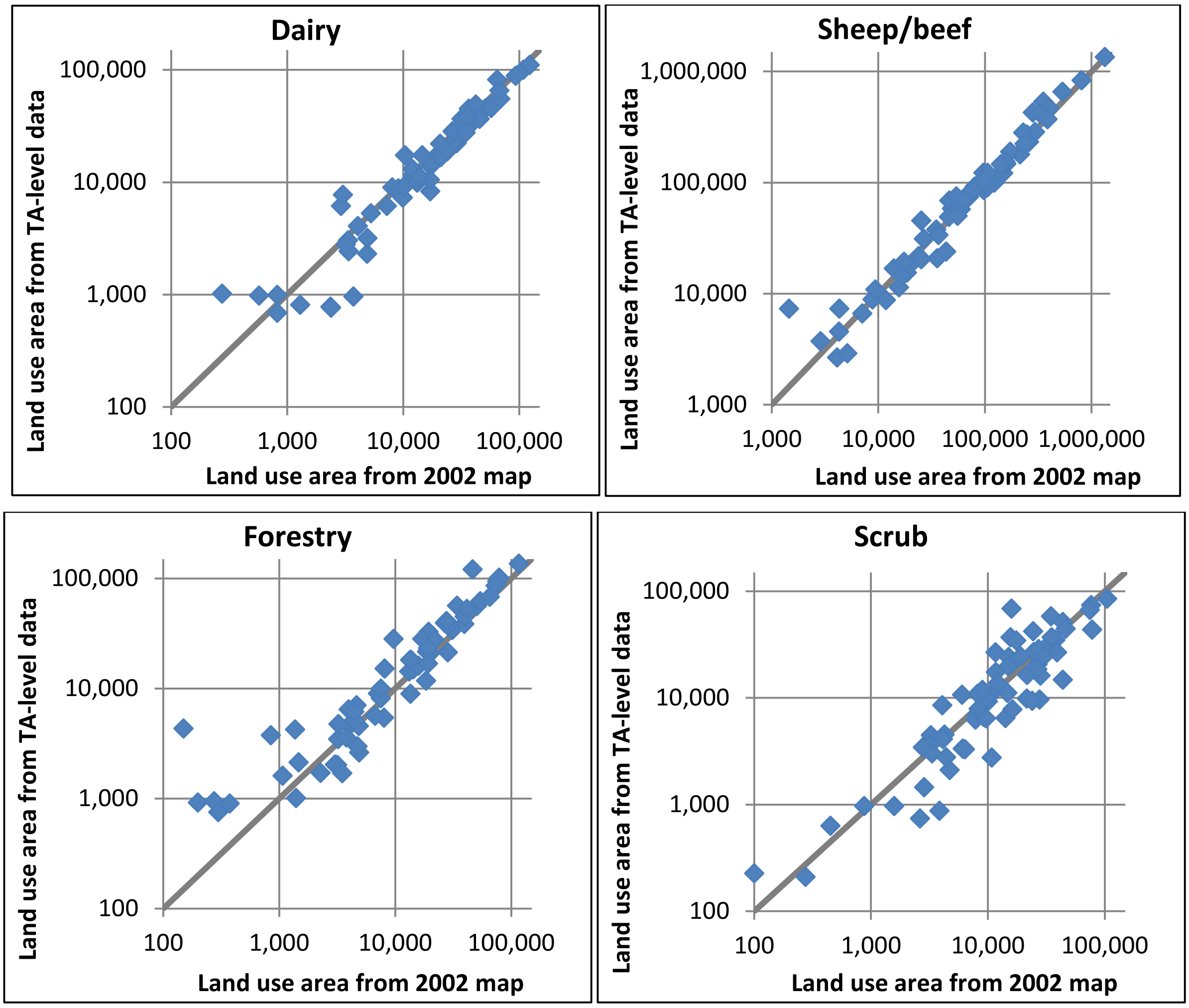
The completed 2002 map is given in Figure 7 and land use by regional council in 2002 is given by Table 10, both of which are in Appendix 1.

2.3. Validating the 2002 Land-Use Map

We assess the validity of the 2002 map with respect to four key land uses: dairy farming, sheep/beef farming, plantation forestry, and scrub. We compare the area in each land use according to the 2002 map with the area according to the TA-level data provided by SNZ, and LIC and DairyNZ. This also helps us assess the consistency of the different datasets.

The land areas used for dairy farming in each TA are given in the Dairy Statistics reports. Panel 1 in Figure 1 compares the dairy areas from the 2002 report with the areas from our constructed 2002 map. The land-use areas are similar to each other at the TA level (that is, the plotted points are close to the 45-degree line). This fit is unsurprisingly worse among those TAs with relatively small quantities of dairy land (such as Tauranga, Papakura, and Christchurch City). In general, the map areas are slightly higher than the areas given by the Dairy Statistics reports. We attribute this to differences in the definition of dairy land between data sources. The areas reported by LIC and DairyNZ are total effective farming areas (and therefore exclude land not explicitly used for dairy farming), while the areas identified by ELCDB2 (and hence in our 2002 map) are the total dairy farm areas.

Figure 1: Comparison of land-use areas between map and survey data (hectares)



The land area used for sheep/beef farming in each TA is defined as the difference between the pasture area reported by SNZ and the dairy area reported by LIC and DairyNZ. The corresponding areas in our 2002 map will be those classified as sheep/beef farming or as public pasture. Panel 2 in Figure 1 compares the sheep/beef areas calculated from each TA with the areas from our constructed 2002 map.[9] Again, the land-use areas are similar at the TA level.[10] The fit is not as good among those TAs with relatively small quantities of sheep/beef land (such as Waitakare, Hamilton, and Lower Hutt City), as expected.

Panel 3 in Figure 1 compares the plantation forest areas from the 2002 SNZ report with the areas from our constructed map. Again the land-use areas are similar and the consistency between the datasets is worse among urban TAs.

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[9] The scales of the axes for Panel 2 are an order of magnitude larger than for the other three panels.

[10] This is true even though the SNZ pasture numbers include land used to graze other animals. However, the pasture area dedicated to other animals is very small, relative to the area dedicated to sheep or beef.

SNZ also reports scrub land in each TA. In Panel 4 of Figure 1 we again observe that land-use areas from the two datasets are similar. We attribute the differences between the map and TA-level data to differences in classification. Farmers reporting to SNZ may classify as indigenous forest some of the land classified as scrub in LCDB3 (Griffiths 2002; Trotter *et al.* 2005) and may classify some unused land as scrub while we classify it as sheep/beef.

2.4. Construction of the 2008 Land-Use Map

Given the classification of land uses above, the map of land use in 2002, LCDB3's land-cover maps for 2008, and TA-level dairy areas, we construct a map of land use in 2008. The construction of this map is similar to the construction of the 2002 map except in the division of pastoral land cover among dairy, sheep/beef, and other animal farming.

Public land in 2008 (both public pasture and non-pasture land) is identified using the same ownership and CCAV maps, and following the same process, as for the 2002 land-use map (as described in Section 2.2). This means that there is no change in public land between our 2002 and 2008 maps (however, some land may move between public pasture and DoC and public land (excluding pasture)). This seems to be a reasonable assumption, since we expect changes in public land to be sluggish.

To consider the spatial distribution of pastoral land uses, we first assign initial land uses from the 2002 map. Pastoral land in 2008 that was classified as dairy or other animal and lifestyle properties in 2002 is assigned to its respective land use. All other pastoral land in 2008 is assumed to be sheep/beef farming. This gives us a 2008 land-use map with 2002 pastoral land uses. We estimate pastoral land use in 2008 by spatially allocating changes in dairy (and hence sheep/beef land) from 2002 to 2008 according to the LURNZ allocation algorithm. Due to data limitations, land used for other animals and lifestyle properties is assumed to remain constant.

The amount of land (measured as effective hectares) used for dairy farming in each TA in 2008 is given by Livestock Improvement Corporation and Dairy New Zealand (2009). In these datasets, TAs that contain fewer than five dairy herds have been merged with neighbouring TAs to preserve anonymity (see Table 15). We consider TAs separately or in pairs as necessary to be consistent with the data. In addition, we do not consider pastoral land-use change in those TAs that are small and predominantly urban.[11] After adjusting for the difference between total and effective hectares, annual changes in dairy land are calculated for each TA using simple linear

[11] These TAs are: the North Shore, Waitakere City, Auckland City, Porirua City, Lower Hutt City, and Wellington City.

trends between the areas given from the 2002 map and the areas from the dairy reports.[12] Changes in sheep/beef land are assumed to be equal and opposite.

Simple linear trends are used as this reduces the year-to-year fluctuations in reported land-use areas. This minimises the "churning" or reshuffling of land use while still resulting in the correct final quantity of each land use.[13] We minimise churning as rural land-use change is a slow and costly process (Kerr and Olssen 2012) and churning increases the amount of land-use change that takes place.

The TA-level changes in pastoral land are spatially allocated within each TA using the LURNZ allocation algorithm. For the construction of the 2008 map we constrain the algorithm (given in Section 3.2) to allow only changes in dairy and sheep/beef land, and to simulate at the TA level. The completed 2008 map is given in Figure 8 and land use by regional council is given in Table 11, both of which are in Appendix 1.

3. The Spatial Allocation of Land-Use Change

Given annual changes in (regional or national) land-use areas, the LURNZ allocation algorithm assigns these changes across space. The allocation algorithm focuses on only four land uses: dairy, sheep/beef, plantation forestry, and scrub land. These are historically New Zealand's major rural land uses. In this section we describe our conceptual model of land-use conversions, before detailing the algorithm that determines the spatial pattern of land-use changes.

3.1. Conceptual Model

Consider the use of land for dairy, sheep/beef, plantation forestry, and scrub. In general, the more intensive land uses have higher costs but also higher payoffs from production. If the quality of the land determines its productivity and hence its profitability, then profit-maximising landowners will select their land use according to the quality of their land (consider, for example, Figure 2). Hence, the more intensive land uses will be more likely to occur on higher-quality land.

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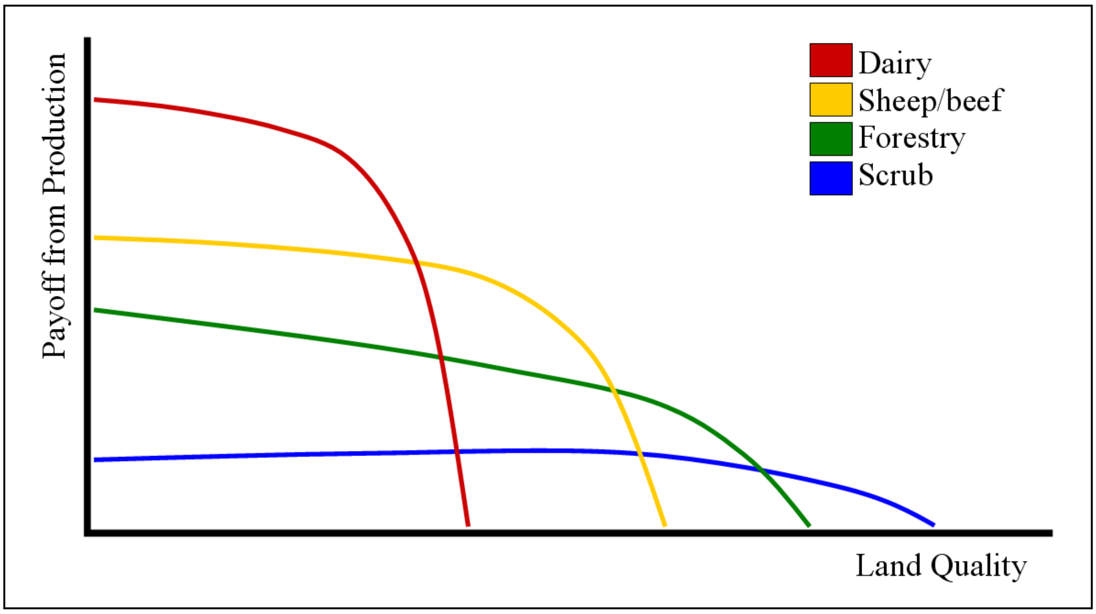
[12] The adjustment between total and effective hectares is done before the annual changes were fed into the model. The adjustment is based on the ratio of total to effective hectares in 2002, the only year we observe total hectares for dairy. The ratio of total to effective hectares is approximately 1.07; this is the factor that was used to adjust dairy areas for all years.

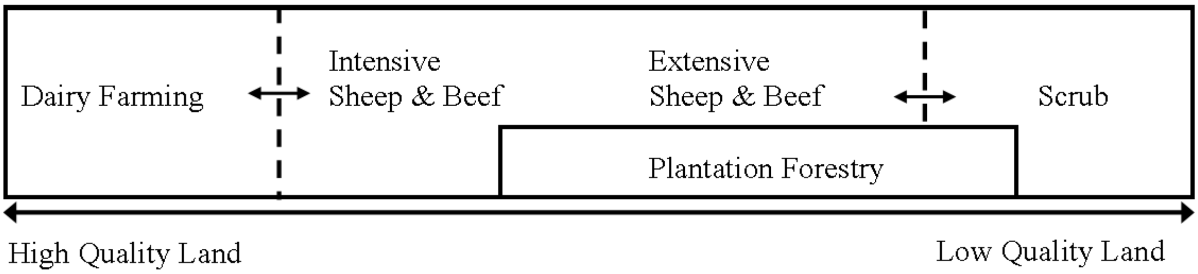
[13] The "churning" of land use occurs in LURNZ where the location but not the quantity of land-use changes. Churning of land can occur across years (for example, a decrease in dairy land one year followed by an increase in dairy land the following year) and within a single year (for example, where forestry is converted to dairy land, and then sheep/beef land is converted to forestry).

Figure 2: Conceptual model of returns to different land uses as land quality falls



It follows that, if we arrange land along a continuum by land quality, then the best-quality land will be used for the most intensive land use (dairy farming) and the worst-quality land will be left as unproductive scrub. The thresholds between uses are defined by the intersection of the relative return curves. The remaining land will be split between sheep/beef farming and plantation forestry. How much of the best land is used for dairy will depend on the returns from dairy farming relative to the returns from intensive sheep/beef farming. How much of the worst land is left as scrub will depend on the returns from scrub relative to the returns from extensive sheep/beef farming and plantation forestry. Because land quality is not one dimensional and sheep/beef farming is not homogenous, forestry and sheep/beef are not so easily distinguished. Figure 3 suggests how they might be divided spatially.

Figure 3: Conceptual model of land use by land quality



Plantation forestry occurs on similar quality land to extensive sheep/beef farming. However, unlike sheep/beef farming, there are high costs associated with land-use change for forestry: Converting land into forestry involves giving up the potentially significant option value of pastoral land (easier conversion to dairy, lifestyle, or urban), while converting land out of forestry before the plantation has reached maturity reduces the return from harvest.

In contrast, there may be low costs for converting land between extensive sheep/beef farming and scrub land. When returns to sheep/beef farming are low, a farmer could close off less productive paddocks, allowing them to revert to scrub. When returns to sheep/beef farming are high, the farmer would open up these closed-off paddocks and clear scrub, enabling more animals to be grazed over the increased area.

Conversion to dairy farming is characterised by high costs. Establishing a new dairy farm entails significant costs associated with the purchase of capital for milking. These costs occur irrespective of the previous land use. Converting from dairy farming into sheep/beef farming is characterised by much lower costs, as the new sheep/beef farm will use the established pasture.

For LURNZ, this implies that conversions involving forestry land should occur less frequently than other land-use changes; it should be easy for conversions between sheep/beef farming and scrub land to occur; and if land is converted from dairy farming, then it is most likely to convert to sheep/beef farming.

3.2. The LURNZ Allocation Algorithm

The LURNZ allocation algorithm has been significantly revised since the original version reported by Hendy *et al.* (2007). Indicators of the suitability (based on observable land characteristics) of a pixel for dairy farming, sheep/beef farming, plantation forestry, and scrub are given by probabilities of the pixel being in each land use. These probabilities are estimated for each pixel by a multinomial logit model of land-use choice, according to the methodology by Timar (2011). Estimated coefficients are given in Table 16 in Appendix 2. For any given land use, those pixels with the greatest probability are considered most suitable, while those pixels with the smallest probability are considered the least suitable.

For each year, given the total change in each land use, the allocation algorithm assigns changes in land use to pixels in three steps. In order, these steps consider changes in dairy land, changes in sheep/beef land, and changes in forestry land. We consider changes in this order as it gives priority to the land uses that are more profitable. Changes in scrub land occur as a consequence of changes in the other land uses. The allocation algorithm is as follows:

Step 1.a: If dairy land increases, then the sheep/beef, plantation forestry, and scrub land that have the highest dairy probabilities change to dairy land, subject to two additional controls on plantation forestry (given below).

Step 1.b: If dairy land decreases, then the dairy land with the lowest dairy probabilities changes to sheep/beef land (and is possibly subject to further change in step 2).

Step 2.a: If sheep/beef land increases, then the plantation forestry and scrub land that has the highest sheep/beef probabilities changes to sheep/beef land, subject to two additional controls on plantation forestry (given below).

Step 2.b: If sheep/beef land decreases, then the sheep/beef land (including any land released from dairy during step 1) with the lowest sheep/beef probabilities changes to scrub land (and is possibly subject to further change in step 3).

Step 3.a: If plantation forestry land increases, then the scrub land (including any land released from sheep/beef during step 2) with the highest forestry probabilities changes to plantation forestry.

Step 3.b: If plantation forestry land decreases, beyond any conversion of land in steps 1 and 2, then the forestry land with the lowest forestry probabilities changes to scrub land.

The conversion of plantation forestry to dairy or sheep/beef is subject to two additional controls as follows. First, LURNZ tracks the age of forestry on each pixel in each year.[14] Only those pixels that are identified as being of harvestable forest age (aged 26 to 32 years) or as awaiting replanting (age zero) may change land use.[15]

Second, at steps 1 and 2, if forestry land is increasing, no forestry land may change to dairy or sheep/beef. On the other hand, if forestry land is decreasing then the amount of forestry land that changes to dairy and sheep/beef must not exceed the total decrease in forestry land (for example, if sheep/beef land is increasing, forestry is decreasing by 150 hectares overall and 50 hectares of forest was converted to dairy land during step 1, then at most 100 hectares of forestry land can change to sheep/beef land during step 2).

The algorithm allocates only changes in land use each year. This minimises the number of pixels that change use. There are two reasons why we do not reallocate all land use each year. First, land-use change is a slow process and there are costs associated with transitions between land uses. Allocating only changes minimises the “churning” or reshuffling of land uses. Second, many unobservable factors drive land use and our models are unable to explain perfectly current land use.

[14] The age of plantation forestry in 2008 is determined by Zhang and Kerr (2011).

[15] A proportion of forest pixels of harvestable age are harvested each year. Pixels that have been harvested but not yet replanted are classified as “awaiting replanting”. A fixed proportion of pixels that are awaiting replanting are replanted each year.

Two further points may impact the use of LURNZ in some applications. First, because the algorithm allocates only changes each year the LURNZ results exhibit some path dependence.[16] Second, the controls on the conversion of forestry mean that the algorithm described above does not allow for premature harvesting when there are, for example, strong pressures to deforest and convert to dairy.

4. Validating the Allocation Algorithm

This section presents the validation of the LURNZ allocation algorithm. We use the 2002 map and data at the national level on net changes in land use to simulate a 2008 map and then compare that to observed 2008 land cover and TA land use. Changes in land cover between 2002 and 2008 can be observed from LCDB3, while changes in TA-level dairy area are observed in the LIC and DairyNZ data. As these datasets have been used solely to inform the construction of our baseline maps, and have not informed the design of the allocation algorithm, it is appropriate to use these to validate the LURNZ allocation algorithm.

As only 2 percent of land cover changes between 2002 and 2008, we conduct our validation by analysing only those changes, for example deforestation and afforestation. We combine dairy and sheep/beef land into a single category (pasture) post simulation, except for the TA-level comparison with LIC and DairyNZ data. We observe dairy and sheep/beef in 2002, so we can observe pixels that both leave dairy or sheep/beef and leave a pastoral land cover in 2008. We also observe pixels that move into a pastoral land cover in 2008.

Table 7 gives the observed changes in land cover, between 2002 and 2008.

For our validation, we specify net land-use change at the national level and allow the spatial allocation algorithm to allocate the changes around New Zealand. This is how change is spatially allocated when LURNZ is used to simulate future land-use change scenarios.[17] We utilise a variety of data sources on land areas to estimate annual net changes in national land use between 2002 and 2008. These year-to-year changes are scaled such that the total amount of net land-use change that is specified matches the observed changes in land cover between the 2002 and 2008 maps. The annual changes are shown in Table 17 in Appendix 2.

[16] This path dependence does not appear to be significant when results are aggregated to TAs.

[17] We omit the control that only forestry of harvestable age and forestry that is awaiting replanting can change land use. This control is omitted due to the limitations of our 2008 forestry age map.

Table 7: Observed changes in land cover between 2002 and 2008 according to LCDB3 ('000s ha)

	Pasture 08	Forestry 08	Scrub 08	Horticulture 08	Urban 08	Other exogenous 08	Total exogenous 08	Total
Dairy 02	1,557	2	1	18	1	<1000	19	1,578
Sheep/beef 02	7,243	47	13	210	5	1	217	7,520
Pasture 02	8,799	48	14	229	6	2	236	9,098
Forestry 02	77	1,355	4	1	<1000	1	2	1,438
Scrub 02	106	15	1,160	7	<1000	1	10	1,290
Horticulture 02	34	<1000	<1000	204	<1000	1	239	239
Urban 02	0	0	0	0	176	0	176	176
Other exogenous 02	2	3	1	16	1	14,373	14,397	14,397
Total exogenous 02	36	3	1	457	185	14,377	15,018	14,812
Total	9,019	1,422	1,179	457	185	14,377	15,018	26,638

Notes: The row "Pasture 02" is the sum of "Dairy 02" and "Sheep/beef 02", and is not included in the vertical sums; similarly for "Total exogenous".

For dairy, we used the LIC and DairyNZ data on dairy areas by TA from 2002 to 2008. For sheep/beef, we used SNZ agricultural production survey data on pasture area (less dairy and public pasture) from 2002 to 2008, and scaled the annual changes such that the sum of annual changes in dairy and sheep/beef land matched the observed change in pastoral land cover between 2002 and 2008. For forestry, we used the National Exotic Forestry Description (NEFD) data on new planting and deforestation, scaled to match changes in the observed spatial data.[18] Scrub changes were calculated residually to offset the changes in dairy, sheep/beef, and forestry. Some of the endogenous land pixels in 2002 moved into an exogenous land use in 2008, and vice versa. Because we do not have an algorithm to allocate urban or other exogenous land uses, and because scrub changes absorb residual change in the spatial algorithm, these changes are absorbed into the annual scrub changes used in the validation simulation. The net change in the exogenous land use areas between 2002 and 2008 was 206,500 hectares, while the net change in observed scrub areas over the same period was -110,325 hectares, so this induces a large error in the scale of scrub changes. It does not, however, affect the validation of the location of scrub changes.

Table 8 gives the changes in land cover areas between the 2002 map and the simulated 2008 map. Comparing observed (Table 7) to simulated land use, we can confirm that at the national level the total area of pasture and forest are equal in 2002 and 2008, while the simulated area of scrub matches in 2002 but exceeds the observed area in 2008 because it absorbs changes in exogenous land.

Table 8: Simulated changes in land cover – national-level allocation ('000s ha)

	Pasture 08	Forestry 08	Scrub 08	Total
Dairy 02	1,575	<1000	3	1,578
Sheep/beef 02	7,358	10	1525	7,520
Pasture 02	8,933	10	155	9,098
Forestry 02	18	1,397	23	1,438
Scrub 02	68	15	1,207	1,290
Total	9,018	1,421	1,386	11,826
Notes: see notes to Table 7.				

18 The NEFD does not report deforestation for 2003. We used the data from Karpas and Kerr (2011) for our deforestation figure for 2003.

Table 9 shows the differences between the simulated changes and the observed changes. We observe that our allocation algorithm tends to under allocate changes from pasture land to forestry. It also tends to under allocate changes from forestry into pasture. However, the amount of scrub land allocated to forestry almost exactly matches the observed transitions of scrub to forestry. Our algorithm also does well in simulating the amount of land that remains in its initial land use. The largest error occurs for scrub, where we over-allocate land remaining in scrub by 4%. The numbers in the row and column labelled "Total" are equal to the amount of land transitioning between an endogenous and exogenous land use, which are allocated to changes in scrub in the validation exercise.

Table 9: Differences between simulated and observed transitions ('000s ha and % of observed)

	Pasture 08	Forestry 08	Scrub 08	Exogenous land use
Dairy 02	18 (1.15%)	-1.5 (-88.24%)	3 (309.09%)	19
Sheep/beef 02	116 (1.60%)	-37 (-79.47%)	139 (1030.48%)	217
Pasture 02	134 (1.52%)	-39 (-79.78%)	141 (988.79%)	236
Forestry 02	-59 (-76.84%)	42 (3.08%)	19 (511.92%)	2
Scrub 02	-39 (-36.31%)	<1000 (-0.17%)	47 (4.06%)	8
Exogenous land use	36	3	207.5	

Notes: The level number is the difference (simulated − observed transitions) in hectares. The percentages (in parentheses) were calculated by taking the difference between simulated and observed land-cover transitions, as a percentage of the observed transitions. For example, the 1.52% figure for pasture land in 2002 that remains in pasture in 2008 says that our simulation overallocates land remaining in pasture by about 1.5% of the observed quantity of land that remains in pasture. The column and row labelled "Exogenous land use" is equal to the sum of the differences and represents the transitions into and out of an exogenous land-use class. "Pasture 02" is not included in the vertical sum. "Pasture 02" is not included in the vertical sum.

We now discuss the performance of the allocation algorithm with respect to the quality of land and the location where land-use change takes place.

4.1. Validation by Land Quality

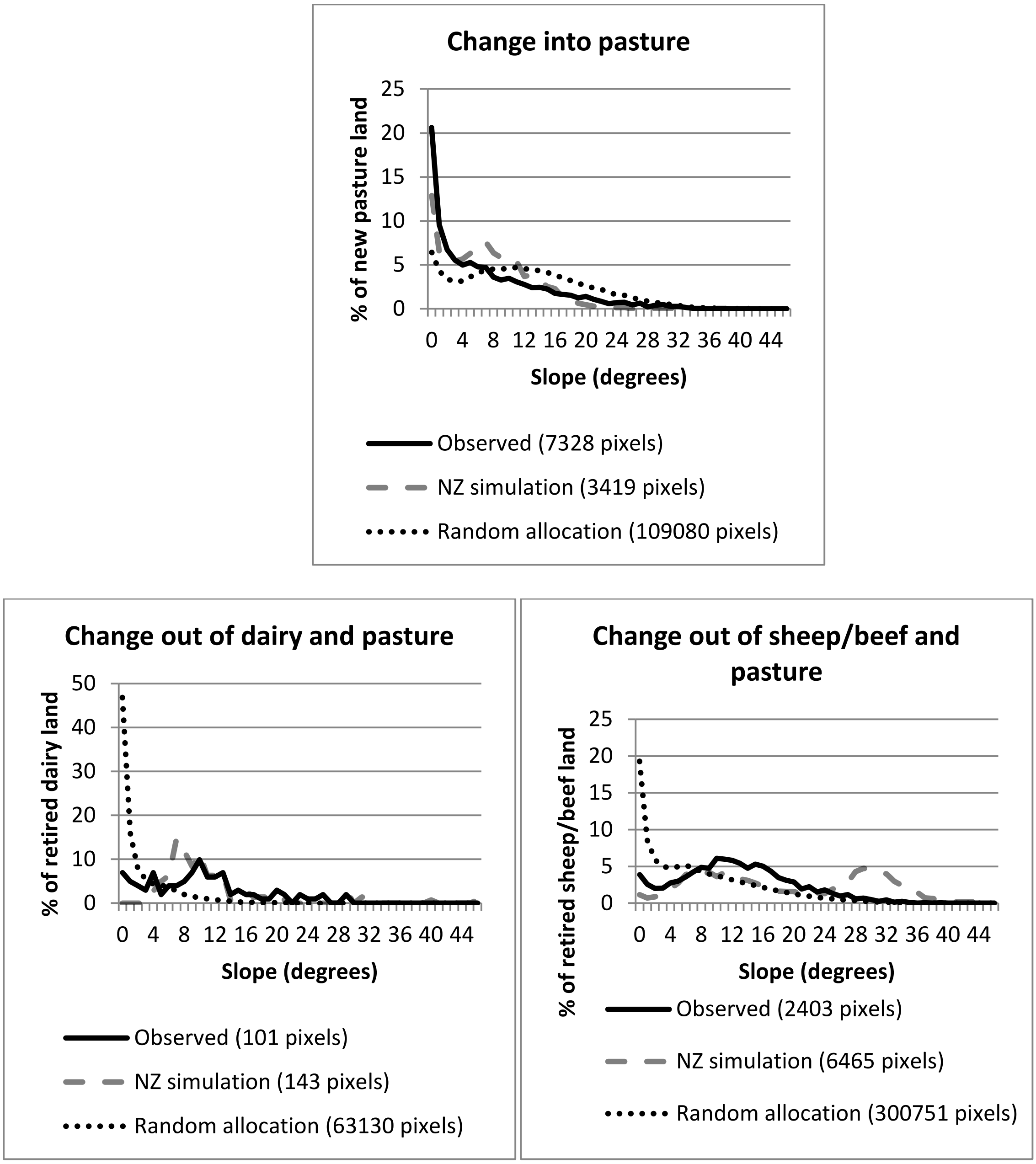
We can have confidence in the algorithm if it allocates changes in land use to land that is of similar quality, or has similar properties to the land where land-cover change did occur. We therefore consider the distribution of changes in land cover with respect to slope and CCAV. An indication of the validity of the allocation algorithm will be that simulated changes in land cover are distributed over a similar range of slope and CCAV values as the observed changes in land cover.

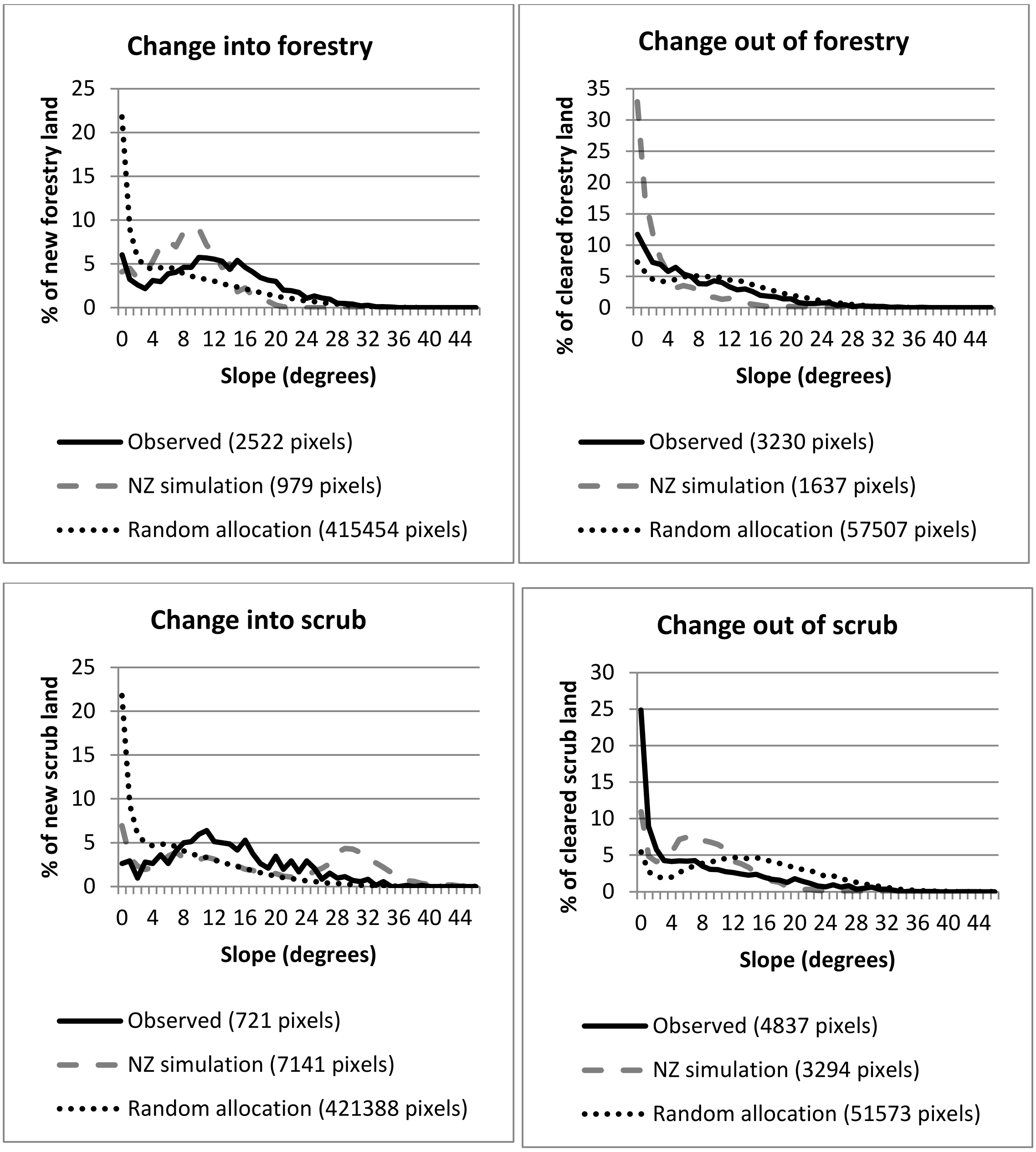
Figure 4 gives the distribution of slope for each type of land-use change.[19] Slope is one of the land attributes that is used to construct the pixel probabilities for the allocation algorithm. To aid our comparisons, we include the distribution of slope that would arise if changes were allocated on a completely random basis.[20]

[19] These distributions have been constructed as histograms with 1 degree of slope bucket widths. For ease of viewing these have been displayed as curves with a three-point moving mean.

[20] The random allocation is the distribution of slope and CCAV for all pixels. This assigns land-use change based on the proportion of total land with a given value of slope or CCAV.

Figure 4: Distribution of slope for each type of land-use change





We observe that the LURNZ allocation algorithm results in land-cover change occurring on land with similar distributions of slope to the land where land-use change was observed. For almost all changes the allocation algorithm provides a better distribution than could be accomplished by random allocation. Relative to the random allocation, the algorithm moves the distribution of land in the direction of the observed land use in nearly all cases. It generally overcompensates because the model allows for less idiosyncratic variation than we observe in reality. This might seem to suggest that we should introduce more randomness into our model, and this would improve the fit on this measure, but it would make the model worse in other respects.

For land moving into pasture, the peak of the observed distribution occurs on flat land. This is also where the peak of the simulated distribution occurs. However, we tend to overallocate land moving into pasture on more moderately sloped land (between 5 and 10 degrees). The peak of the observed distributions for land leaving pasture (separated into dairy and sheep/beef) occurs on moderately sloped land (approximately 10 degrees). We tend to slightly overallocate land leaving dairy (and pasture) on land with a slope between 5 and 10 degrees, while matching the observed distribution closely for steeper slopes.[21] For land leaving sheep/beef (and pasture), the simulated distribution matches the observed distribution quite well. However, we tend to overallocate land leaving sheep/beef on relatively steep land.

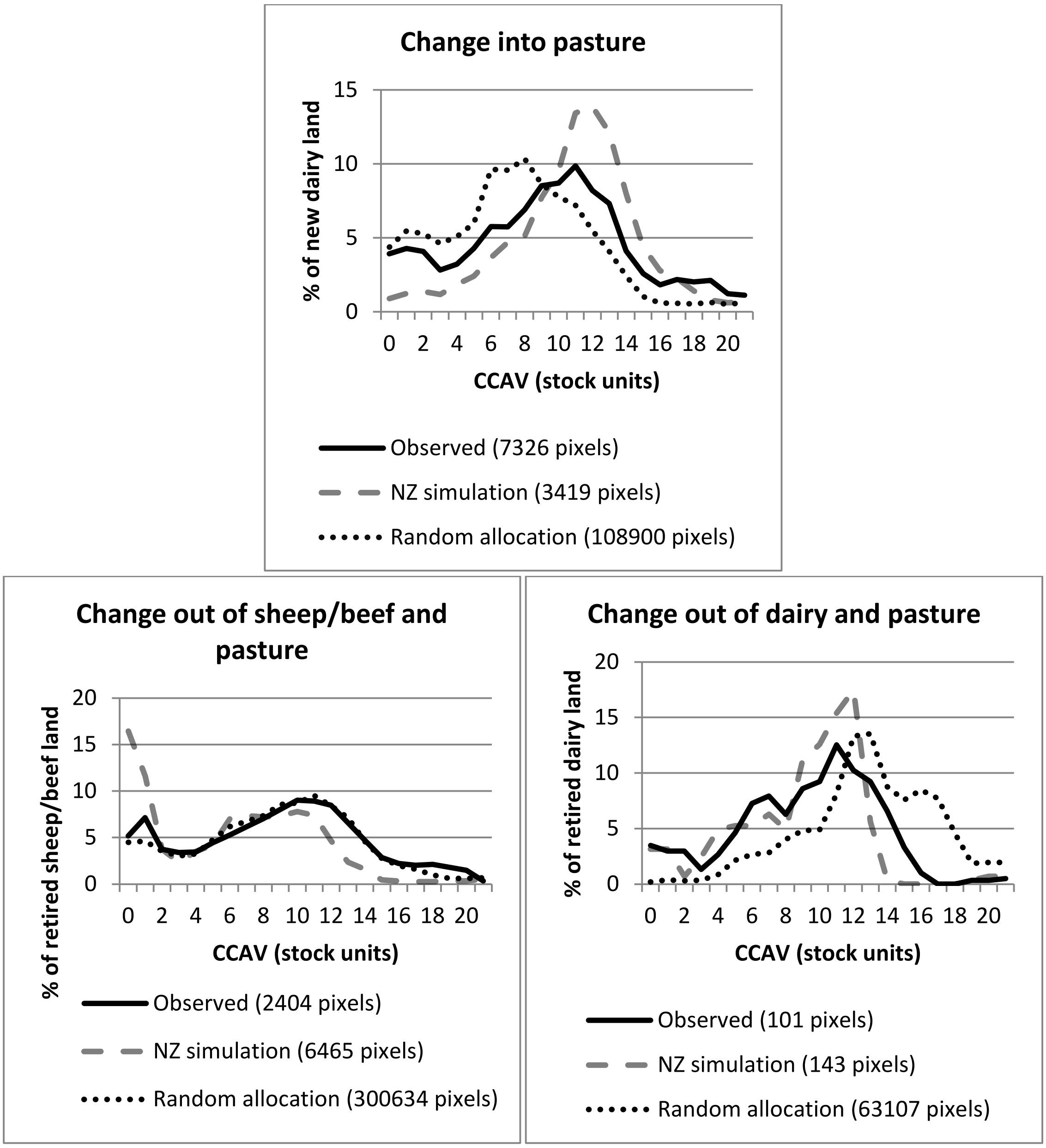
We observe land moving into forestry on moderately sloped land (10–15 degrees). The simulated distribution has a very similar shape, although we tend to overallocate forestry on slightly flatter land, while underallocating on steeper land. Flat land accounts for most of the land observed as leaving forestry. The simulated distribution has a similar shape to the observed, but overallocates on flat land while underallocating on steeper land.

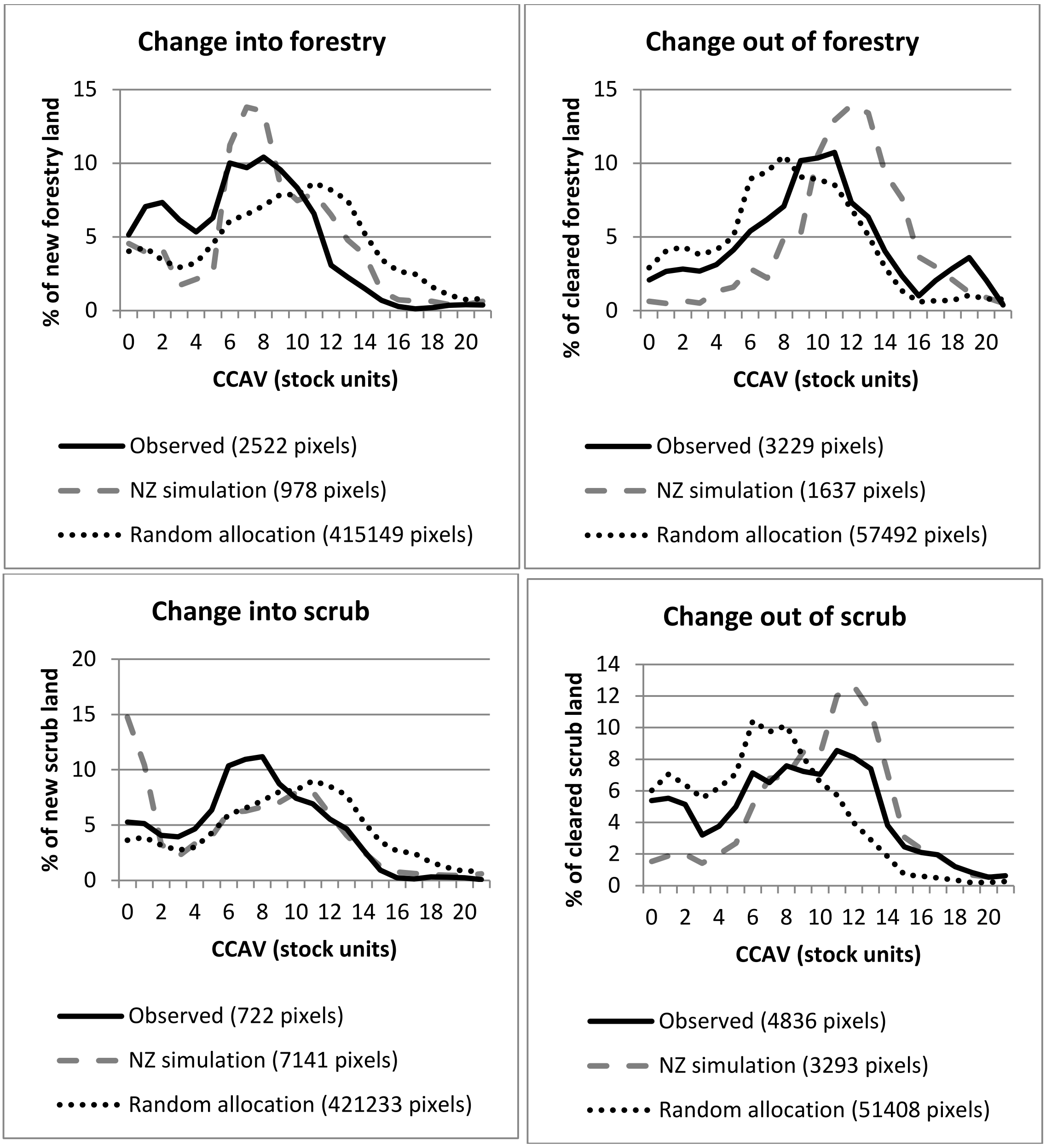
We observe moderately sloped land (around 10 degrees) being abandoned to scrub. This is most likely sheep/beef land that has been allowed to revert. Our simulation matches the observed distribution well for relatively flat land (<5 degrees); it tends to underallocate scrub reversion on more moderately sloped land. Scrub clearing happens mostly on relatively flat land – this is the land most suited to pastoral activities. The simulated distribution matches the observed closely, except for the slight overallocation of land moving out of scrub on moderately sloped land.

Figure 5 gives the distribution of CCAV for each type of land-use change. CCAV is not one of the land attributes that is used to construct the pixel probabilities for the allocation algorithm. We again include the distribution of CCAV that would arise if changes were allocated on a completely random basis.

[21] The observed and simulated distributions of land moving out of dairy (and pasture) are based on a relatively small number of pixel changes (101 and 143, respectively).

Figure 5: Distribution of CCAV for each type of land-use change



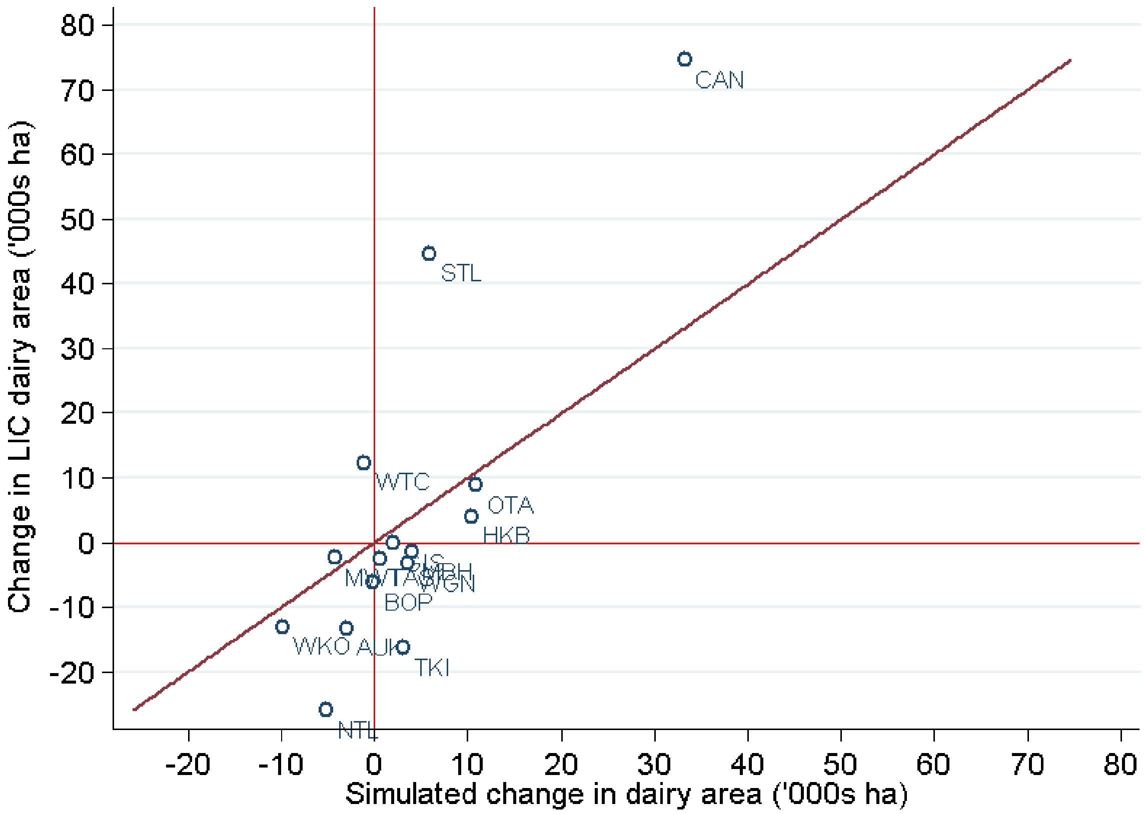


We observe that the LURNZ allocation algorithm results in land-cover change occurring on land with similar distributions of CCAV to the land where land-use change was observed. For almost all changes the allocation algorithm provides a better distribution than could be accomplished by random allocation. We tend to overallocate changes into and out of pasture on land with moderate values for CCAV (between 10 and 14). This patterns also holds for transitions into and out of forestry. We underallocate transitions into scrub on land with relatively low values for CCAV (between 4 and 8), while overallocating transitions out of scrub on land with moderate values.

4.2. Validating Dairy Changes by TA

We cannot compare the characteristics of the land that we simulate moving into dairy to observed movements into dairy because we have no land-use map for 2008. However, we can at least check that we are simulating increases (decreases) in dairy land in regions that actually experience an increase (decrease) in dairy land. Figure 6 below plots the simulated changes in dairy against the changes in dairy area from the LIC and DairyNZ data by regional council, including a 45-degree line for reference.

Figure 6: Simulated versus observed changes in dairy area by regional council[22]



There is a relatively strong positive correlation between simulated and observed changes in dairy area by regional council. In general, we get the direction of change correct; however, we do not do so well with the magnitude of the changes. This is clear when we consider Canterbury (CAN) and Southland (STL). Dairy land in Canterbury was simulated to increase by 40,000 hectares. But in reality it increased by double that amount – around 80,000 hectares. Likewise, we simulated an almost 10,000-hectare increase in dairy land in Southland, when in fact the actual increase was around 45,000 hectares. These are relatively new areas for dairy, so this land

[22] See Table 18 in Appendix 2 for the explanation of the regional council abbreviations.

use may be on land with different characteristics from the 2002 dairy land we based our model on. In addition, were unable to control for irrigation, or the potential for irrigation, in those estimates, and expansion of irrigation has been critical for dairy conversions in some areas. There is a small cluster of regional councils where we simulate a small increase, when in fact these areas experienced a slight decrease in dairy area.

While we generally place new dairy land in the right regional councils, we do not necessarily place it in the right TA within the regional council. When we examine the TA-level changes we do find a statistically significant positive relationship between observed and simulated changes in dairy area. There is a lot of noise in the relationship however; the R^2 from the regression is only 0.07. Our algorithm allocates increases in dairy land from (non-dairy) pixels with the highest probability of being in dairy – which TA or regional council these pixels happen to be in does not inform our algorithm. Local policies, such as zoning or water-quality policies, could affect which pixels are allowed to move into dairy in the real world – this could partially explain the discrepancies in the magnitude of changes between the observed and simulated changes.

5. Conclusion

This paper documents the development of land-use maps for 2002 and 2008, records the design of the LURNZ allocation algorithm, and presents a validation of the allocation algorithm. As a national-level model of land-use change in New Zealand, LURNZ provides a useful tool for informing government, industry, and stakeholder decision making.

The baseline map of land use in 2002 was derived from observed land cover reported by LCDB3 and land use reported by ELCDB2. Pasture on public land and other public land (including land owned by DoC) was identified according to a map of land under public ownership. The land-use areas in our 2002 map for dairy, sheep/beef, plantation forestry, and scrub land were a good match with the areas reported at a TA level by SNZ, DairyNZ, and LIC.

The baseline map of land use in 2008 was derived from observed land cover reported by LCDB3. Public land (pasture and non-pasture) was identified according to the same map of land under public ownership used in the construction of the 2002 map. Pasture land cover was initially divided into different land uses based on its use in 2002, before changes in dairy and sheep/beef land from 2002 to 2008 were simulated within each TA.

The baseline land-use maps for LURNZ are consistent with observed land cover in 2002 and 2008, are consistent with observed land use in 2002, and are consistent with TA-level land-use areas in 2002 and 2008. We can therefore have confidence in the accuracy of these maps.

The LURNZ allocation algorithm is one of the key parts of the LURNZ model. In this paper we have both described our conceptual model of land-use change, and documented how this model is implemented in LURNZ to allocate land-use change spatially.

The validation of the LURNZ allocation algorithm shows that simulated land-cover change occurs on land with similar distributions of slope and CCAV to the land where land-cover change is observed. For almost all changes the allocation algorithm provides a better distribution than could be accomplished by random allocation. We also show that our algorithm allocates changes in dairy to TAs where changes in dairy are actually observed, though we do not predict the scale of dairy expansion in Southland and Canterbury.

This validation has also enabled us to identify three areas for improvement that could be made to the allocation algorithm. First, the conversion of pasture land to forestry, and conversion of forestry to pasture (a significant feature of this particular historical period because of climate change legislation), are both significantly underestimated by the model. We do allocate these changes on the right sort of land on the whole. We could calibrate the model to allow more churn in forest land. This could be particularly useful if we use the model for Monte Carlo simulations. Second, some low-quality pasture land may be unlikely to change in use unless high-quality pasture on the same property also changes use. This, and other spatial effects such as clustering of forest land, would require an algorithm that is spatially explicit. Finally, for studies where changes in scrub area are important, it is critical that we begin to model changes in horticulture explicitly.

As nations' populations increase and the demand for resources and agricultural production correspondingly increase, land will become an increasingly important resource. Knowing the spatial distribution of land use and the expected location of future land-use change is important for informed decision making. By documenting and validating LURNZ, we hope to make the model more accessible to those who could benefit from its use, and to encourage the further development of land-use modelling in New Zealand.

6. References

Anastasiadis, Simon, Marie-Laure Nauleau, Suzi Kerr, Tim Cox, and Kit Rutherford. 2011. "Does Complex Hydrology Require Complex Water Quality Policy? NManager Simulations for Lake Rotorua". *Motu Working Paper* 11-14. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/ publications/working-papers.

Anastasiadis, Simon, Suzi Kerr, Adam Daigneault, Graeme J. Doole, Suzie Greenhalgh, Oscar Montes de Oca Munguia, Daniel Rutledge, and James Turner. 2013. "Understanding the Practice of Land Use Modelling". Report prepared for the Parliamentary Commissioner for the Environment. Motu Economic and Public Policy Research.

AsureQuality. 2008. "AgriBase Enhanced LCDB2". Dataset obtained by Motu Research in 2008. http://www.asurequality.com/capturing-information-technology-across-the-food-supply-chain/agribase-products-that-show-land-cover.cfm.

———. 2010. "Rural Database Enhanced by Geospatial Technology." http://www.asurequality.com/capturing-information-technology-across-the-food-supply-chain/agribase-products-that-show-land-cover.cfm.

Daigneault, Adam J., and Fraser Morgan. 2012. "Estimating Impacts of Climate Change Policy on Land Use: An Agent Based Modeling Approach". 2012 Annual Meeting, August 12–14, 2012, Seattle, Washington 124973. Agricultural and Applied Economics Association. http://ideas.repec.org/p/ags/aaea12/124973.html.

Daigneault, Adam, Suzie Greenhalgh, Oshadhi Samarasinghe, and Robyn Sinclair. 2011. "Estimating Co-Benefits of Agricultural Climate Policy in New Zealand: A Catchment-Level Analysis." 2011 Annual Meeting, July 24-26, Pittsburgh, Pennsylvania 103885. Agricultural and Applied Economics Association. http://econpapers.repec.org/paper/agsaaea11/103855.htm

Filatova, Tatiana, Anne van der Veen, and Dawn Parker. 2009. "Land Market Interactions between Heterogeneous Agents in a Heterogeneous Landscape—Tracing the Macro-Scale Effects of Individual Trade-Offs between Environmental Amenities and Disamenities." *Canadian Journal of Agricultural Economics/Revue Canadienne D'agroeconomie* 57(4): 431–57.

Griffiths, A.D. 2002. "Indigenous Forestry on Private Land: Present Trends and Future Potential". *MAF Technical Paper* 01/6. Wellington: Ministry of Agriculture and Forestry.

Hamilton, Christopher, Sebastian Martinuzzi, Andrew Plantinga, Volker Radeloff, David Lewis, Wayne Thogmartin, Patricia Heglund, and Anna Pidgeon. 2013. "Current and Future Land Use around a Nationwide Protected Area Network." *PloS One* 8(1): e55737.

Heistermann, Maik, Christoph Muller, and Kerstin Ronneberger. 2006. "Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land-Use Modeling." *Agriculture, Ecosystems and Environment* 114: 141–58.

Hendy, Joanna, Suzi Kerr, and Troy Baisden. 2007. "The Land Use in Rural New Zealand Model Version 1 (LURNZv1): Model Description". *Motu Working Paper* 07-07. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/publications/working-papers.

Hertel, Thomas W., Steven Rose, and Richard S.J. Tol. 2009. "Land Use in Computable General Equilibrium Models: An Overview." In *Economic Analysis of Land Use in Global Climate Change Policy*, edited by Thomas W. Hertel, Steven Rose, and Richard S.J. Tol, pp. 3-30. Oxford: Routledge.

Karpas, Eric, and Suzi Kerr. 2011. "Preliminary Evidence on Responses to the New Zealand Forestry Emissions Trading System". *Motu Working Paper* 11-09. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/publications/detail/preliminary_evidence_on_responses_to_the_new_zealand_forestry_emissions_tra.

Kerr, Suzi, and Alex Olssen. 2012. "Gradual Land-Use Change in New Zealand: Results from a Dynamic Econometric Model". *Motu Working Paper* 12-06. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/publications/detail/gradual_land-use_change_in_new_zealand_results_from_a_dynamic_econometric_m.

Landcare Research. 2002. "Average Carrying Capacity (CCAV) Map". Dataset obtained by Motu Research in 2002.

———. 2004. "Land Environments of New Zealand (LENZ) Map 2002". Dataset obtained by Motu Research in 2004.

———. 2008. "Ownership Map of New Zealand 2002". Dataset obtained by Motu Research in 2008.

———. 2012. "Land Cover Database v3.0". Dataset obtained by Motu Research in 2012. https://lris.scinfo.org.nz/layer/401-lcdb-v33-land-cover-database-version-33.

Landcare Research, and Ministry of Agriculture and Fisheries. 2002. "Land Use Capability (LUC) Map 2002". Dataset obtained by Motu Research in 2002.

Leathwick, John, Fraser Morgan, Gareth Wilson, Daniel Rutledge, Malcolm McLeod, and Kirsty Johnston. 2002. "Land Environments of New Zealand: A Technical Guide". Wellington: Ministry for the Environment and Landcare Research.

Livestock Improvement Corporation, and Dairy New Zealand. 2009. "New Zealand Dairy Statistics 2008–09". Hamilton: LIC and DairyNZ. http://www.lic.co.nz/pdf/dairy_stats/DAIRY_STATISTICS_08-09.pdf.

Lubowski, Ruben, Andrew Plantinga, and Robert Stavins. 2006. "Land-Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function." *Journal of Environmental Economics and Management* 51(2): 135–52.

Martinuzzi, Sebastian, Stephanie Januchowski-Hartley, Brenda Pracheil, Peter McIntyre, Andrew Plantinga, David Lewis, and Volker Radeloff. 2014. "Threats and Opportunities for Freshwater Conservation under Future Land Use Change Scenarios in the United States." *Global Change Biology* 20(1): 113–24.

Ministry for the Environment, and Terralink International. 2005. "Land Cover Database v2.0". Dataset obtained by Motu Research in 2005.

New Zealand Climate Change Office. 2004. *New Zealand Land Cover Database 2: User Guide*. Report prepared for the New Zealand Climate Change Office. Wellington: Ministry for the Environment. http://www.mfe.govt.nz/issues/land/land-cover-dbase/index.html.

Parker, Dawn C., Daniel G. Brown, J. Gary Polhill, Peter J. Deadman, and Steven M. Manson. 2008. "Illustrating a New Conceptual Design Pattern for Agent-Based Models of Land Use via Five Case Studies – the MR POTATOHEAD Framework." In *Agent-Based Modelling in Natural Resource Management*, edited by A.L. Paredes and C.H. Iglesias, pp. 23–51. Valladolid: Universidad de Valladolid.

Radeloff, Volker, Erik Nelson, Andrew Plantinga, David Lewis, Davis Helmers, Joshua Lawler, John Withey, Frederic Beaudry, Sebastian Martinuzzi, Van Butsic, Eric Lonsdorf, Dennis White, and Steve Polasky. 2012. "Economic-Based Projections of Future Land Use in the Conterminous United States Under Alternative Policy Scenarios." *Ecological Applications* 22(3): 1036–49.

Statistics New Zealand. 2009. "Statistics New Zealand Land-Use and Livestock Number by Territorial Authority 1980–2008". Dataset obtained by Motu Research in 2009.

Timar, Levente. 2011. "Rural Land Use and Land Tenure in New Zealand". *Motu Working Paper* 11-13. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/publications/working-papers.

Timar, Levente, and Suzi Kerr. 2014. "Land-Use Intensity and Greenhouse Gas Emissions in the LURNZ Model". *Motu Working Paper* 14-03. Wellington: Motu Economic and Public Policy Research. http://www.motu.org.nz/publications/working-papers.

Trotter, Craig, Kevin Tate, Neal Scott, Jacqueline Townsend, Hugh Wilde, Suzanne Lambie, Mike Marden, and Ted Pinkney. 2005. "Afforestation/Reforestation of New Zealand Marginal Pasture Lands by Indigenous Shrublands: The Potential for Kyoto Forest Sinks." *Annals of Forest Science* 62(8): 865–71.

Zhang, Wei, and Suzi Kerr. 2011. "Creating New Zealand Forestry Age Maps in 2002 and 2008 and Estimating and Projecting Plantation Forest Removals and Emissions in LURNZ". Draft manuscript. Wellington: Motu Economic and Public Policy Research.

7. Appendix 1 - Land Use and Land-Use Change

Figure 7: LURNZ 2002 land-use map

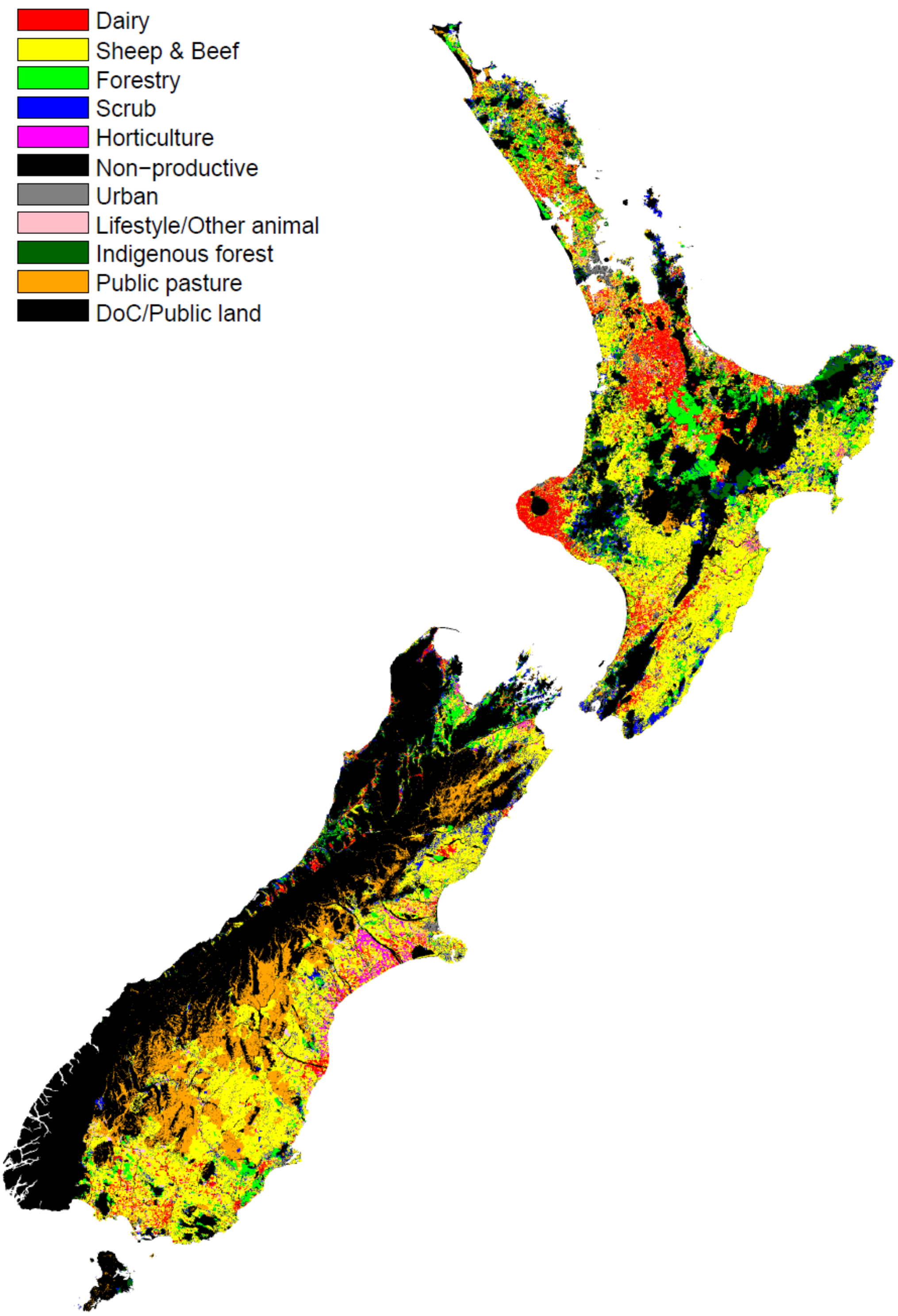


Figure 8: LURNZ 2008 land-use map

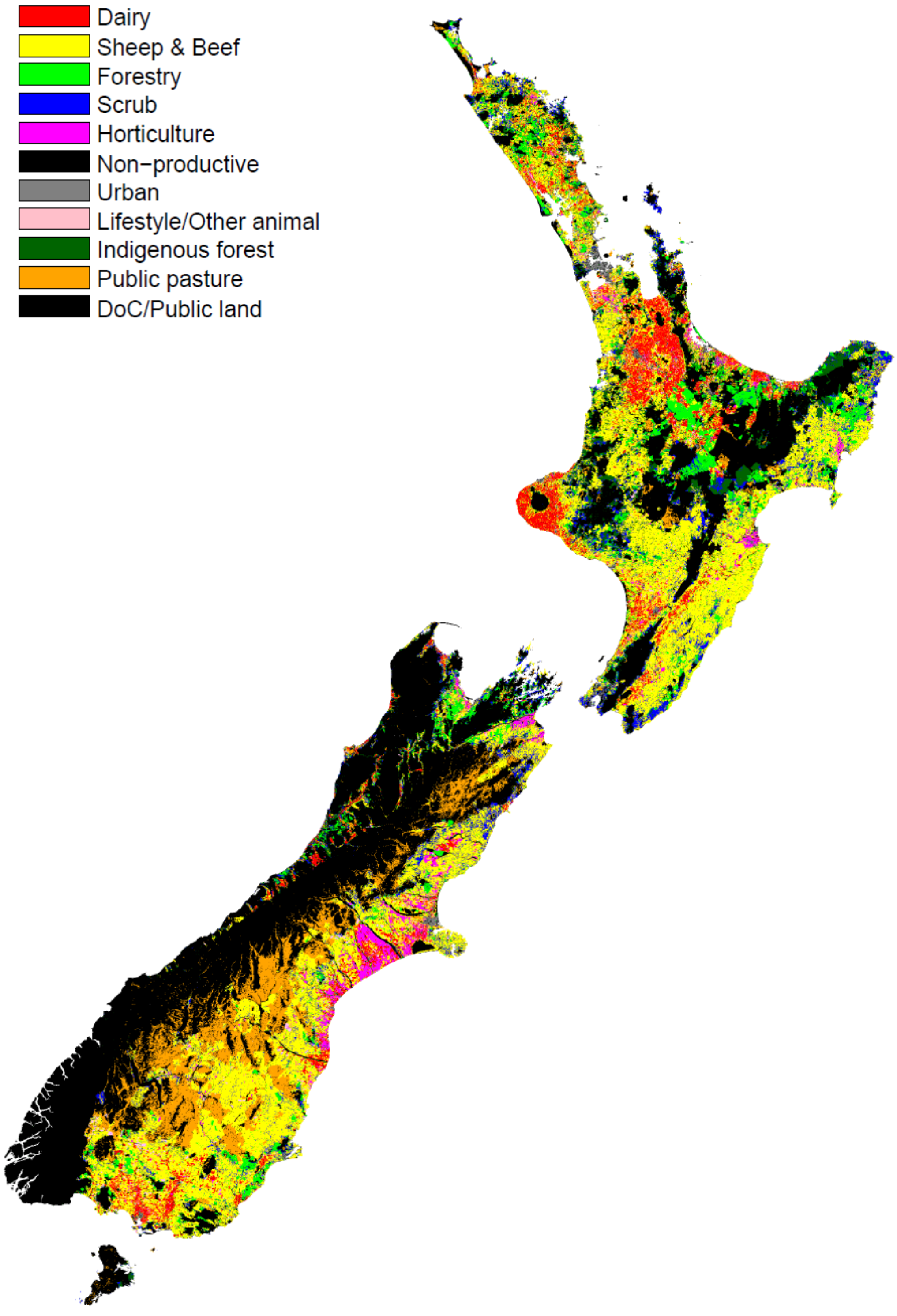


Figure 9: LURNZ land-use change map 2002 to 2008 – original land use

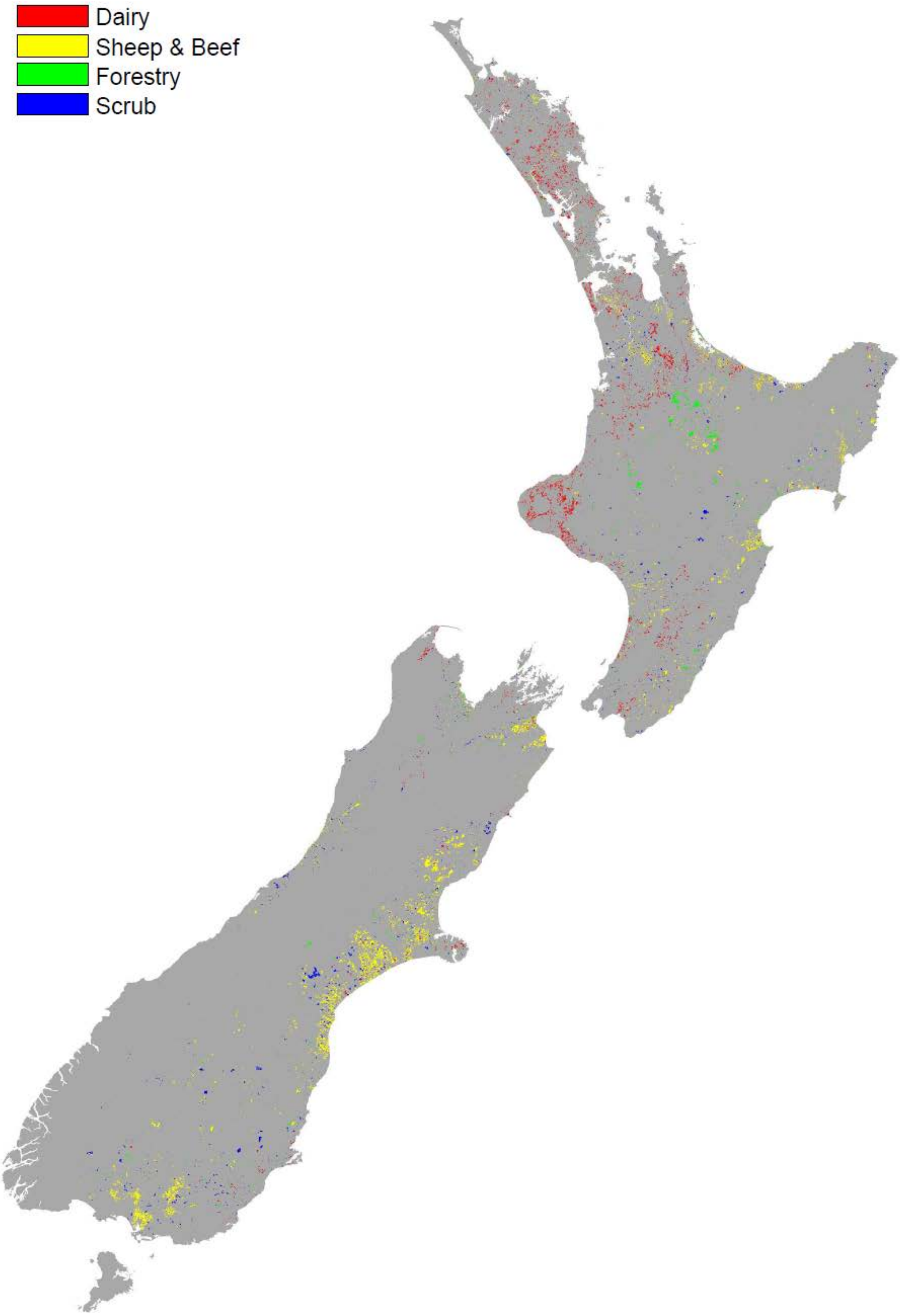


Figure 10: LURNZ land-use change map 2002 to 2008 – final land use

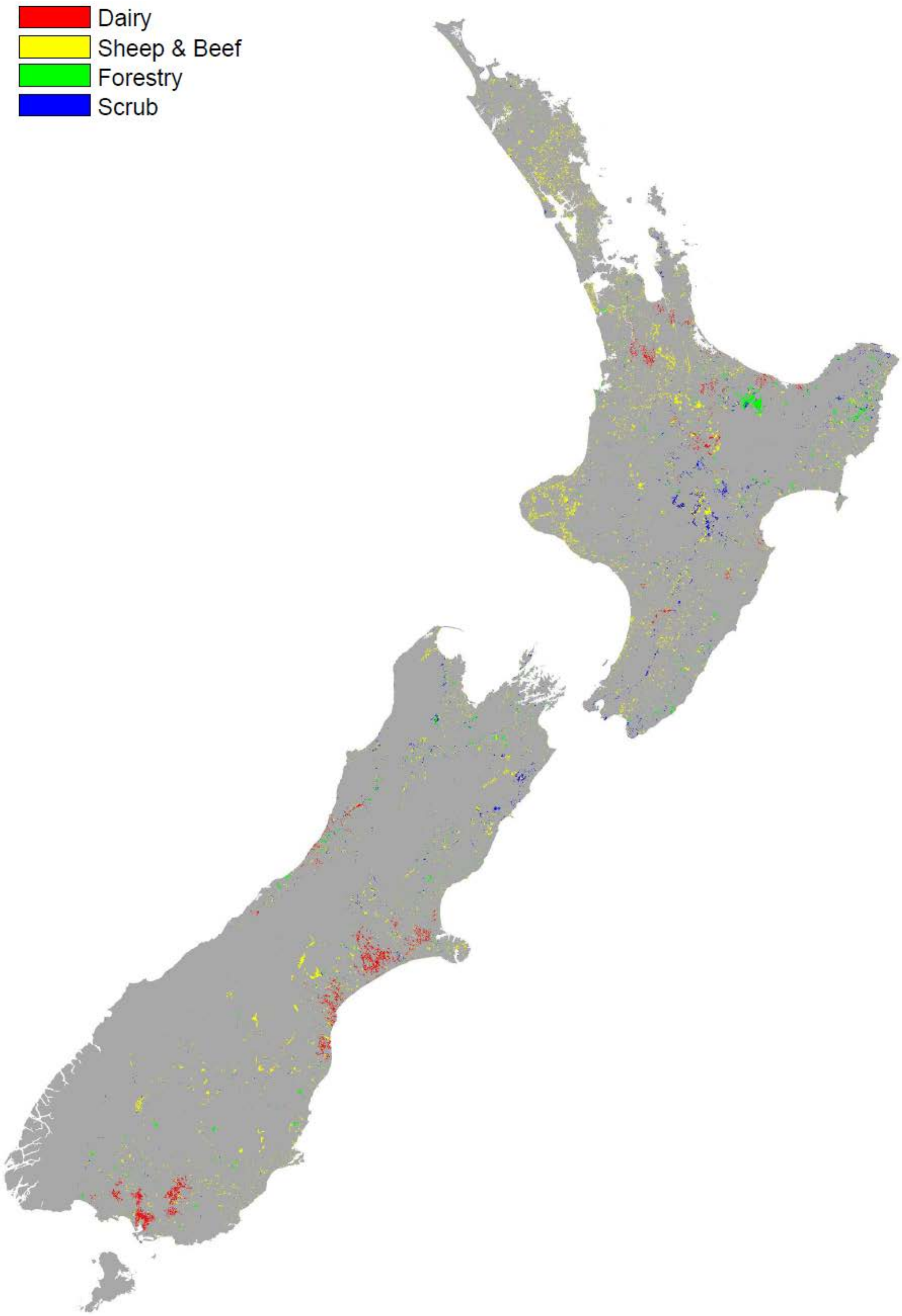


Table 10: Land-use areas by regional council in 2002

Regional council	Dairy (ha)	Sheep/Beef (ha)	Forestry (ha)	Scrub (ha)	Horticulture (ha)	Non-productive (ha)	Urban (ha)	Lifestyle/ Other animal (ha)	Indigenous forest (ha)	Pasture on public land (ha)	DoC and other public land (ha)
Northland	169,800	370,325	146,775	104,650	4,425	29,150	6,900	9,325	132,650	45,500	220,600
Auckland	53,850	154,925	36,250	37,200	5,750	10,100	43,225	17,550	35,850	13,825	86,300
Waikato	478,850	652,225	258,325	112,425	9,775	118,075	20,950	43,250	156,150	69,800	517,425
Bay of Plenty	84,650	134,775	115,675	34,025	11,525	50,875	11,625	13,275	133,700	30,900	601,325
Gisborne	2,375	341,100	116,775	104,400	6,225	57,325	2,375	4,400	58,000	11,800	128,750
Hawke's Bay	16,925	659,400	108,225	91,050	14,150	51,175	6,350	13,625	91,375	26,825	335,000
Taranaki	213,725	148,325	22,975	54,550	1,425	6,125	5,850	7,025	89,450	13,925	161,725
Manawatu-Wanganui	126,750	1,059,475	124,300	128,025	9,000	48,150	12,125	25,125	140,750	60,200	485,125
Wellington	33,750	323,775	49,800	100,075	3,000	17,900	16,175	7,225	23,600	12,725	221,100
West Coast	54,000	55,225	28,650	40,300	75	40,300	2,400	5,725	72,550	30,825	2,003,575
Canterbury	133,550	1,387,375	104,350	202,325	138,375	129,225	25,000	82,950	21,850	820,050	1,467,300
Otago	66,325	1,242,400	121,575	106,825	13,275	97,175	10,350	26,375	14,950	761,400	722,125
Southland	106,625	699,275	71,150	53,900	3,650	28,100	6,375	57,575	38,725	221,675	1,876,900
Tasman	26,775	75,850	71,650	39,150	8,075	23,600	2,225	7,775	44,375	6,350	655,975
Nelson	400	3,650	7,275	4,475	25	375	2,025	175	1,125	900	21,600
Marlborough	9,925	211,850	54,375	76,400	9,875	32,850	2,375	6,000	20,875	140,100	481,525

Table 11: Land-use areas by regional council in 2008

Regional council	Dairy (ha)	Sheep/Beef (ha)	Forestry (ha)	Scrub (ha)	Horticulture (ha)	Non-productive (ha)	Urban (ha)	Lifestyle/ Other animal (ha)	Indigenous forest (ha)	Pasture on public land (ha)	DoC and other public land (ha)
Northland	119,425	425,825	146,900	102,775	9,925	20,500	7,825	8,900	131,925	45,050	221,050
Auckland	34,900	171,400	36,475	36,925	11,300	6,550	44,175	17,125	35,850	13,100	87,025
Waikato	455,600	715,650	247,375	111,150	18,100	81,475	22,450	42,375	155,850	67,575	519,650
Bay of Plenty	86,625	126,300	144,150	40,800	27,350	6,300	12,650	12,375	133,575	29,425	602,800
Gisborne	650	352,200	132,975	113,800	15,300	13,625	2,400	4,000	58,025	11,125	129,425
Hawke's Bay	18,025	664,375	110,725	102,975	33,125	12,525	6,550	12,775	91,200	25,950	335,875
Taranaki	168,100	196,925	23,025	53,500	1,925	3,550	6,075	6,950	89,400	13,925	161,725
Manawatu-Wanganui	110,425	1,098,450	121,900	134,675	16,750	13,950	12,400	24,650	140,500	59,525	485,800
Wellington	26,175	329,675	54,450	104,175	7,850	5,625	16,750	7,125	23,475	12,125	221,700
West Coast	63,225	58,175	36,500	39,450	25	22,600	2,600	5,725	70,925	31,350	2,003,050
Canterbury	193,625	1,293,275	113,675	190,825	245,900	64,100	26,325	75,475	21,800	816,350	1,471,000
Otago	61,500	1,269,875	123,225	94,225	19,875	79,175	10,850	25,750	14,775	766,725	716,800
Southland	155,550	660,300	76,775	45,025	7,275	18,275	6,475	57,050	38,650	220,650	1,877,925
Tasman	20,075	90,125	75,150	43,250	10,575	6,000	2,400	7,650	44,250	6,125	656,200
Nelson	275	3,775	7,275	4,425	25	250	2,225	150	1,125	625	21,875
Marlborough	5,825	205,575	59,050	78,000	31,525	17,050	2,500	4,175	20,825	140,925	480,700

8. Appendix 2 - Map-making Data Description

Table 12: Land Cover Database version 3 (LCDB3) land-cover classes

Numeric code	Land-cover class
1	Built-up Area
2	Urban Parkland/Open Space
5	Transport Infrastructure
6	Surface Mine and Dumps
10	Sand and Gravel
12	Landslide
14	Permanent Snow and Ice
15	Alpine Grass-/Herbfield
16	Gravel and Rock
20	Lake and Pond
21	River
22	Estuarine Open Water
30	Short-rotation Cropland
33	Orchard, Vineyard and Other Perennial Crops
40	High Producing Exotic Grassland
41	Low Producing Grassland
43	Tall Tussock Grassland
44	Depleted Grassland
45	Herbaceous Freshwater Vegetation
46	Herbaceous Saline Vegetation
47	Flaxland
50	Fernland
51	Gorse and/or Broom
52	Manuka and/or Kanuka
54	Broadleaved Indigenous Hardwoods
55	Sub Alpine Shrubland
56	Mixed Exotic Shrubland
58	Matagouri or Grey Scrub
64	Forest – Harvested
68	Deciduous Hardwoods
69	Indigenous Forest
70	Mangrove
71	Exotic Forest

Table 13: AgriBase Enhanced Land Cover Database (ELCDB2) land-use classes

Numeric code	Letter code	Land-use class
1	API	Honey production/processing
2	ARA	Arable cropping
3	AVOC	Avocados
4	BEF	Beef cattle farming
5	BERR	Berryfruit production
6	CITR	Citrus
7	DAI	Dairy milk production
8	DEE	Deer farming
9	DOG	Kennels/catteries
10	DRY	Dairy dry stock rearing
11	EMU	Emu
12	FIS	Aquaculture/fish hatcheries
13	FLO	Cut flower growing
14	FOR	Forestry
15	FRU	Orchards of unspecified type
16	GOA	Goat farming
17	GRA	Grazing other people's stock
18	HAYF	Hay fodder production
19	HERB	Herbs
20	HOR	Horses (equine)
21	KIWF	Kiwifruit orchards
22	LIF	Lifestyle blocks
23	MAIZ	Maize growing
24	NAT	Native forest blocks
25	NOF	Not farmed – idle
26	NUR	Plant nursery
27	NUTS	Nut trees
28	OAN	Miscellaneous animal types
29	OFRU	Other fruits e.g. Cherimoyas
30	OLAN	Other land use e.g. quarries
31	OPL	Other plant types e.g. Meadowfoam
32	OST	Ostrich farming
33	OTH	Other land use not covered elsewhere
34	PIG	Piggeries
35	PIPF	Pipfruit
36	POU	Poultry or egg layers
37	SEED	Seed crops e.g. clover, Lucerne
38	SHP	Sheep farming
39	SNB	Mixed sheep and beef farming
40	SQUA	Squash
41	STON	Stonefruit
42	TOU	Tourism e.g. homestays
43	UNS	Unspecified
44	VEG	Vegetables/market gardening
45	VIT	Viticulture
46	ZOO	Zoological gardens

Table 14: Land ownership classes

Ownership class	Land ownership description	
Privately owned	Landcorp	Maori land cover
	Landcorp and Maori land cover	Maori reserve and Maori land cover
	Private reserve	QEII and Maori land cover
	Transpower	None
Publicly owned	DoC	DoC and LINZ pastoral lease
	DoC and local government	DoC and Maori land cover
	DoC and Ministry of Defence	DoC and QEII
	DoC and QEII and Maori land cover	Unprotected land of interest to DoC
	Landcorp and QEII	LINZ
	LINZ and Landcorp	LINZ and Maori land cover
	LINZ and Ministry of Defence	LINZ pastoral lease
	Local government	Local government and LINZ
	Local government and LINZ and Ministry of Defence	Local government and Maori land cover
	Local government and QEII	Maori reserve
	Ministry of Defence	Ministry of Defence and Maori land cover
	Public reserve	QEII
	Reserve	Reserve and Maori land cover

Table 15: TAs merged with adjacent TAs

Numeric codes	TA name	TA name
25 & 26	Kawerau District	Whakatane District
30 & 31	Napier City	Hastings District
51 & 52	Tasman District	Nelson City
64 & 65	Timaru District	Mackenzie District
68 & 69	Waitaki District	Central Otago District

Figure 11: Trends in dairy farming areas by LIC region

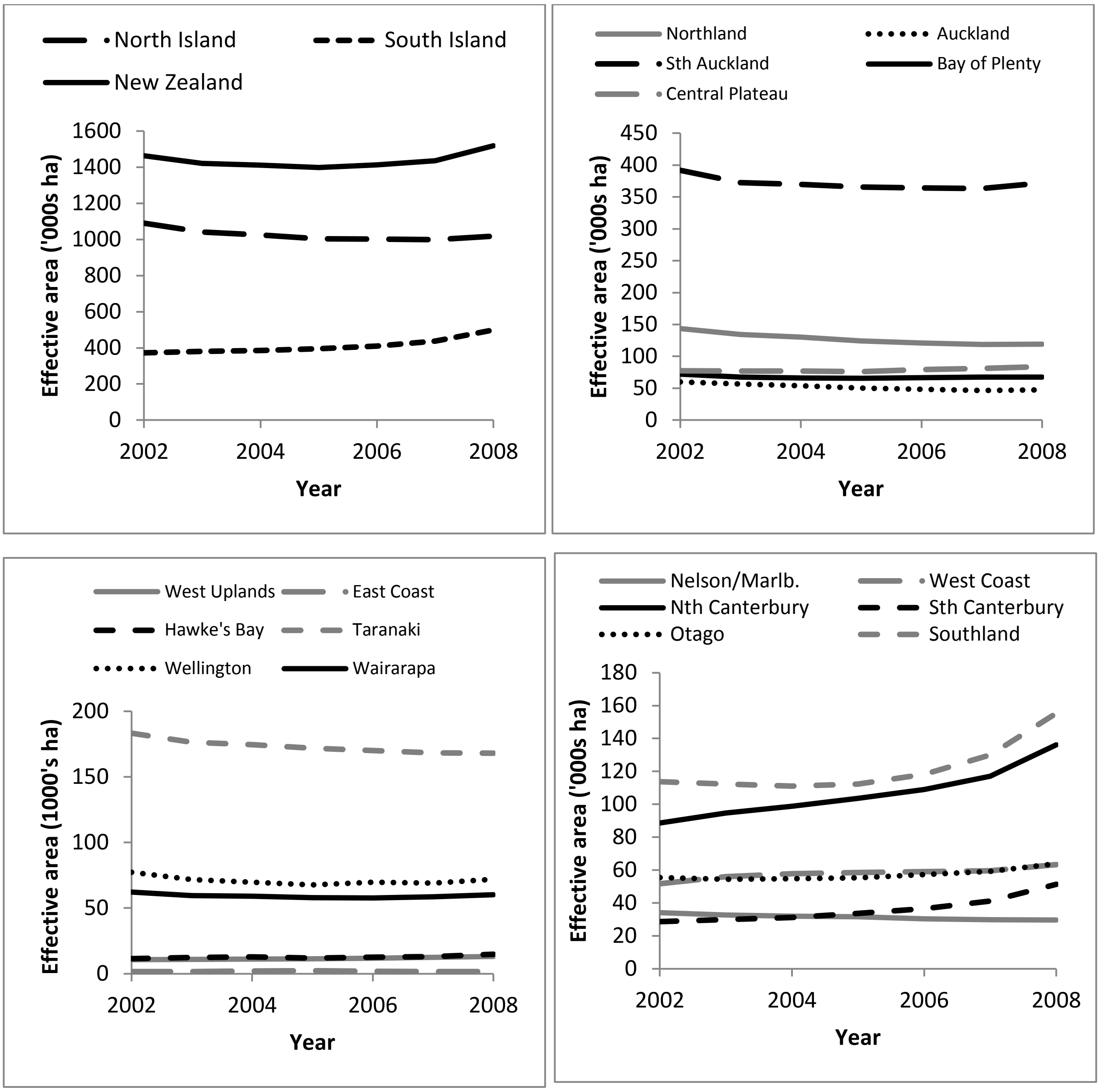


Table 16: Coefficients for calculating land-use probabilities

Coefficients (Timar 2012)	Dairy	Sheep & Beef	Forestry
Slope (degrees)	-0.1823	-0.0629	-0.0564
LUC class	-0.5523	-0.4367	-0.0452
Distance from nearest town (km)	-0.2160	0.0091	-0.0020
Distance from nearest port (km)	-0.0589	-0.0284	-0.0599
Land is Maori owned	-1.9952	-1.7200	-0.5697
Constant	5.1499	4.7599	1.3319

NB: These coefficients are used to calculate the utility of each land use, according to a linear specification. The utility of scrub is always zero. The probability that land is in land use *i* is given by $\frac{e^{u_i}}{\sum_i^n e^{u_i}}$, where u_i is the utility of land use *i* and *n* is the number of land-use types.

Figure 12: Pasture about Lake Rotorua with unknown land use from ELCDB2

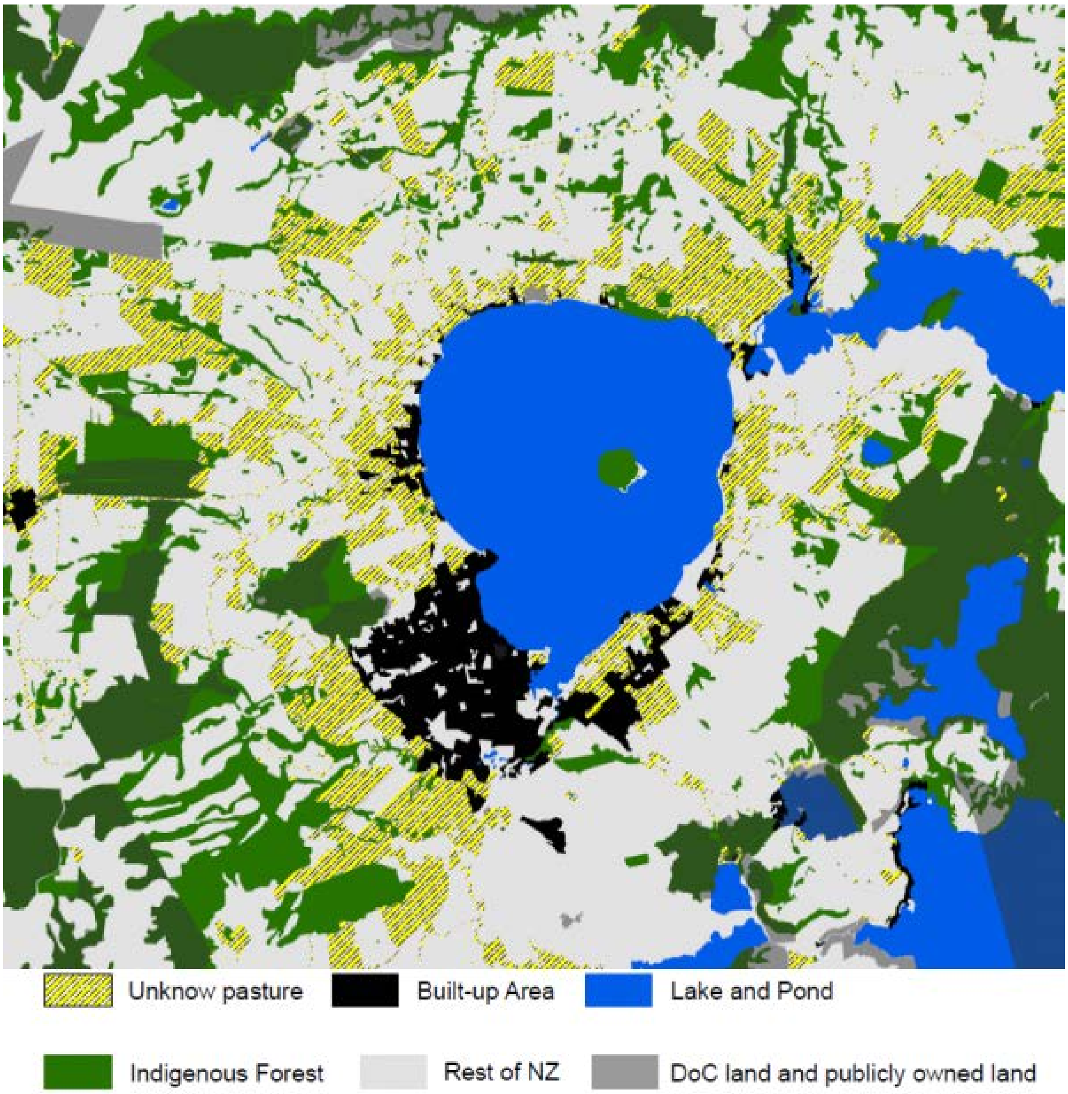


Table 17: National-level changes in land use, for validation simulation

Simulation year	Change in dairy area (ha)	Change in sheep/beef area (ha)	Change in forestry area (ha)	Change in scrub area (ha)
2003	-45,445	-42,775	19600	59550
2004	-10,304	3,725	4750	-225
2005	-13,620	-43,950	-9075	63925
2006	15,056	-38,225	-14475	40650
2007	25,481	20,825	-17,375	-23,850
2008	89,057	-27,550	125	-43,875

Table 18: Regional council abbreviations

Abbreviation	Regional council
NTL	Northland
AUK	Auckland
WKO	Waikato
BOP	Bay of Plenty
GIS	Gisborne
HKB	Hawke's Bay
TKI	Taranaki
MWT	Manawatu-Wanganui
WGN	Wellington
WTC	West Coast
CAN	Canterbury
OTA	Otago
STL	Southland
TAS	Tasman
MBH	Marlborough

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