Manaaki Whenua
Landcare Research

Grassland improvement mapping using Innovative Data Analysis (IDA) techniques

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Grassland improvement mapping using Innovative Data Analysis (IDA) techniques

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Andrew Manderson, Coby Hoogendoorn, Peter Newsome

Manaaki Whenua – Landcare Research

Reviewed by:	*Approved for release by:*
John Dymond	Sam Carrick
Senior Researcher	Portfolio Leader – Characterising Land Resources
Manaaki Whenua – Landcare Research	Manaaki Whenua – Landcare Research

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Summary

Project and Client

The Ministry for the Environment (MfE) has contracted Manaaki Whenua – Landcare Research (MWLR) to investigate the improvement of the managed grasslands classification used in the Land Use and Carbon Analysis System (LUCAS) Land Use Map (LUM).

Project aim

The aim of this project is to investigate improvement of LUM's high- and low-producing grassland classification for the 2008, 2012, and 2016 reporting years, by drawing on techniques developed as part of MWLR's recently completed Innovative Data Analysis (IDA) Endeavour Research Programme (Ausseil et al. 2016).

Methods

- Definitions of high and low producing grassland are reviewed to identify common criteria necessary for classification.
- An investigation has been undertaken to evaluate the potential of using national-scale pasture yield simulation modelling.
- A fuzzy-logic-based framework is developed and implemented to classify high and low producing grassland at the national scale for the 2008, 2012, and 2016 reporting years. Fuzzy logic accommodates the non-metric definition of high- and low-producing grassland, converting criteria to scaled 'degrees of truth' broadly similar to principles of uncertainty and probability. Twelve fuzzy membership layers are developed and combined. Results are aggregated into polygon units used in previous classifications of LUM high and low producing, and assigned a general farm class (dairy, other livestock, and grassland not otherwise used for agriculture).

Results and conclusions

- Definitions of high and low producing grassland are characterised as having criteria that are linguistically vague in both description and specification (e.g. 'low fertility', 'highly productive', typically, generally, mostly).
- Simulation modelling of annual pasture yield has potential as a method to differentiate high and low producing grassland. Several models are available for NZ grasslands. However, management and degree of land development are both major determinants of annual pasture yields. National datasets that adequately represent farm management and land development are unavailable for modelling (they do not exist).
- Fuzzy logic is an expert-guided weights of evidence method useful in applications that have vague specification and/or imprecise data.
- Applied to the classification of managed grassland, the fuzzy logic approach provides a conservative estimate of high producing grassland that is greater than existing LUM estimates but lower than LCDB4 estimates based on remote sensing. This we regard as a positive result, as the LUM classification is based on the now well-dated NZLRI

dataset, and the LCDB4 has a potential to overestimate high producing grassland due to local growing conditions at time of image capture.

- Improved quality and accessibility to national land use data would improve the fuzzy logic classification of high and low producing grasslands.

Recommendations

- That MfE consider the adoption of the fuzzy-logic-based classification of high and low producing grassland for the LUCAS LUM. It represents an improvement over known limitations of the current LUM and LCDB, and provides a conservative estimate based on previous classifications, environmental conditions for pasture growth, and land use type and intensity.
- That those involved with remote-sensing classification of NZ land covers consider using fuzzy logic within their grasslands spectral classification work flow, and/or provide a spectral-based ‘degrees of truth’ layer as an additional source of evidence for use in the fuzzy logic grasslands framework.
- That the New Zealand Government investigates the development of a comprehensive national land use mapping programme providing regular updates to the location and extent of different agricultural land uses across the country.

1 Introduction

The Land Use Map (LUM) is an important component of New Zealand's Land Use and Carbon Analysis System (LUCAS), which is used to estimate greenhouse gas emissions and removals associated with land use as part of NZ's Greenhouse Gas (GHG) Inventory reporting obligations under the Kyoto Protocol and the United Nations Framework Convention on Climate Change.

The LUM itself can be described as spatial database that records the areal representation of 12 land use classes at 4 successive periods (1990, 2008, 2012, and now 2016). Land use mapping first involves automated classification of remotely sensed imagery to determine land use classes that contain woody vegetation, while remaining non-woody classes are identified using other national datasets (MfE 2012, 2018).

Grassland classes are particularly important in a NZ context, as grassland represents 55% of NZ's total land area (MfE 2018), the majority of which (at least 38% of NZ's land area) is used for agricultural purposes (Statistics NZ 2018). Three LUM classes are recognised, including Grassland – with woody biomass (classed from remote sensing), High producing grassland, and Low producing grassland. In LUM the latter two, henceforth referred to collectively as 'managed grassland', are assigned to areas not otherwise classed using other methods, and are differentiated into 'high producing' and 'low producing' using dominant pasture type drawn from the NZ Land Resource Inventory (NZLRI):

> The NZLRI database was used to better define the area of high-and low-producing grassland. Areas tagged as 'improved pasture' in the NZLRI vegetation records were classified as grassland – high producing in the land-use maps. All other areas were classified as grassland – low producing. (MfE 2012, p. 10)

The NZLRI is an older dataset, mostly prepared during the mid-1970s to late-1990s (Lynn et al, 2009). While it may provide an appropriate differentiation of high and low producing grassland for the baseline reporting year (1990), patterns and intensity of pastoral agriculture have changed considerably since this period. These changes are not yet fully reflected in the LUM for 2008, 2012, or 2016 reporting dates.

1.1 Project aim

This project aims to investigate improvement of LUM's high and low producing grassland classification for the 2008, 2012, and 2016 reporting years, by drawing on techniques developed as part of Manaaki Whenua Landcare Research's (MWLR) recently completed MBIE-funded Innovative Data Analysis (IDA) Endeavour Research Programme (Ausseil et al. 2016).

1.2 Report overview

The purpose of this report is to document the process of developing the improved managed grasslands classification:

1 Definitions of high and low producing grassland are briefly reviewed to identify common criteria necessary for classification.

2 An investigation has been undertaken to evaluate the potential of using national-scale pasture yield simulation modelling.

3 A new classification of managed grassland is developed based on fuzzy logic within a geospatial framework.

2 High and low producing grassland definitions

Definitions of high and low producing grassland are provided with LUM documentation. However, the key auxiliary dataset used to differentiate these classes – the NZLRI – has slightly different definitions, and these definitions have been modified and refined overtime. Additionally, the Land Cover Database (LCDB) has similar classifications, with their own particular definitions. All definitions contain multiple criteria to help separate the two classes. A brief review is undertaken to clarify definitions, and identify key criteria and thresholds that are used in the classification of high and low producing grassland.

2.1 Current LUM method

In the current LUM, high and low producing grasslands are classed using the dominant pasture recorded in the vegetation codes of the NZLRI. Two vegetation code versions are available from the NZLRI. The first associates with 1st Edition NZLRI mapping undertaken between 1973 and the late 1980s. This is recorded in the VEG field, and represents approximately 86% of NZLRI coverage. The second version supersedes the first, and applies to most 2nd Edition NZLRI mapping undertaken during the 1990s. This is recorded in the VEG2 field, and represents 14% of NZLRI coverage.

The vegetation classifications available in the NZLRI have their own respective definitions.

2.2 LUM high and low producing grassland

The LUM definitions contain limited detail in terms of classification criteria (Table 1). Potential criteria include pasture species, topography (hill vs non-hill country), and grass-like vegetation types (tussock, herbfields, dune vegetation).

Table 1 LUCAS LUM definitions for high and low producing grassland (MfE 2019)

Grassland – high producing	*Grassland – low producing*
• Grassland with high quality pasture species • Includes linear shelterbelts which are <1 ha in area or <30 m mean width (larger shelterbelts are mapped separately as grassland – with woody biomass) • Areas of bare ground of any size which were previously grassland but, due to natural disturbances (e.g., erosion) have lost vegetation cover	• Low fertility grassland and tussock grasslands • Mostly on hill country • Montane herbfields at either an altitude higher than above timberline vegetation or where the herbfields are not mixed up with woody vegetation • Includes linear shelterbelts which are <1 ha in area or <30 m mean width (larger shelterbelts are mapped separately as grassland – with woody biomass) • Other areas of limited vegetation cover and significant bare soil including erosion and coastal herbaceous sand dune vegetation

Differences in annual production between pasture species is well established (e.g. Suckling 1960), but no national dataset of species distribution is available for this project. 'Hill country' is a colloquial term that is difficult to define in measurable terms and generally encompasses a range of different typologies depending on the scale of definition. Further, fertility transfer and pasture improvement practices, especially in recent decades, can significantly increase pasture productivity in hill country.

2.3 High and low producing pasture (1st Edition NZLRI)

Two definitions are sourced for NZLRI 1st Edition vegetation definitions (Tables 2 and 3). Both provide additional, albeit slightly different, criteria for classification, including environmental conditions that may be useful for a classification framework. However, other than pasture species, most of the offered criteria require further definition especially regarding classification thresholds.

Table 2 NZLRI 1st Edition definitions from NWASCO (1979)

High producing pasture (P1)	*Low producing pasture (P2)*
'Sown pasture' – Pasture with a medium to high dry matter production. Includes ryegrass and white clover	'Adventive grassland' – Includes native grasses and browntop and other pasture species with low dry matter production

Table 3 NZLRI 1st Edition definitions and criteria from Hunter & Blaschke (1986)

High producing pasture (P1)	*Low producing pasture (P2)*
"Sown pasture, dominated by introduced grasses and/or herbaceous legumes, capable of maintaining high levels of production." • Ryegrass/white clover pastures, but also cocksfoot, timothy, crested dogstail, paspalum, kikuyu, red clover, lucerne. • Class is explicitly defined in terms of indicator species rather than dry matter production • Widespread throughout lowlands. Lesser extent on montane arable land. Occurs on much hill country.	"Pasture dominated by grasses and other herbs, generally not capable of maintaining high levels of production." • Browntop, sweet vernal, and danthonia are common species, plus Yorkshire Fog, Poa annua, hairgrasses, brome grasses, chewings fescue • Widespread in extensively grazed montane and lowlands, particularly in hill country • Reflects limited pastoral development, low soil fertility, low soil moisture • 'Naturalised' species (cf. P1)

2.4 Improved and semi-improved pasture (2nd Edition NZLRI)

In the second edition NZLRI the vegetation classification was considerably modified (Newsome 1992), with a change in naming and improved definition (Table 4). Thresholds are provided for pasture production and soil fertility (as Olsen P), and irrigated pasture is included.

Table 4 NZLRI 2st Edition definitions and criteria from Lynn et al. (2009)

Improved pasture (gI)	*Semi-improved pasture (gS)*
Sown legume-based pastures maintaining high levels of pasture production (>10,000 kgDM/ha). Pastures are typically perennial and short rotation ryegrass /white clover dominant, but also include prairie grass, tall fescue, cocksfoot, phalaris, red clover and paspalum and kikuyu in northern districts. Soil fertility would be in the optimum range (Olsen P 20–35). Includes irrigated pastures and lucerne.	Pasture dominated by low fertility grasses, generally capable of maintaining only low levels of pasture production (3,000–8,000 kgDM/ha). Common grasses are brown top, sweet vernal and danthonia. Also included are Yorkshire fog, fescue and *Poa annua*, and white clover, annual clovers, *Lotus pedunculatus* and *L corniculatus*, plantain and other herbs and mosses. Soil fertility would be below optimum with Olsen P <15.

2.5 Land Cover Database (LCDB) definitions

The Land Cover Database (LCDB) also classifies high and low producing grassland, but differs from LUM in that the classification is based on remote sensing and spectral classification. LCDB estimates for High Producing Exotic Grassland are generally much higher than estimates for the LUM equivalent of High producing grassland. This may be attributable to seasonal differences and conditions at time of image capture that shift the spectral signatures of certain low producing species into high producing signatures.

While classification methods differ, the LCDB definitions offer new and more contemporary criteria for consideration (Table 5).

Table 5 LCDB4 definitions (Thompson et al. 2003)

High Producing Exotic Grassland	*Low Producing Grassland*
This class comprises areas of exotic grassland characterised by a spectral signature indicating good vigour of the vegetation cover. Typically, these areas are intensively managed exotic grasslands, rotationally grazed for wool, lamb, beef, dairy, and deer production. These pastures are usually found on land that can be cultivated and are subject to a 'long-rotational' cycle with pasture renewal every 5–10 years. Productivity is enhanced through fertiliser application and in some areas, irrigation. Dominant species are usually clovers and highly productive pasture grasses, such as and cocksfoot. However, the class also includes areas of extensively managed exotic grasslands that show lush growth due to inherently high soil fertility or high annual rainfall. In these grasslands, low productive grasses, such as browntop and sweet vernal, can be dominant.	This class comprises areas of exotic and indigenous grasslands characterised by a spectral signature indicating lower plant vigour and biomass compared to High Producing Exotic Grassland. The reduced vigour reflects lower levels of inherent soil fertility, lower fertiliser application, seasonal drought, or a shorter growing season, especially in the South Island. Typically, the class comprises extensively managed grasslands grazed for wool, sheep-meat and beef production. It is usually found on steep hill and high country throughout New Zealand, often intermixed with areas of High Producing Exotic Grassland on more accessible and fertile sites. Dominant species are less productive exotic grasses, such as browntop and sweet vernal, usually mixed with indigenous short tussock species. Areas of Low Producing Grassland show a tendency to 'brown off' during summer months. Paddock size is generally larger. In wetter areas, scrub reversion is evident on sites less accessible to stock.

2.6 Summary

A common feature of the definitions reviewed is the inclusion of criteria or descriptions that are imprecise in their specification (e.g. 'low fertility', 'highly productive', typically, generally, mostly). Only the definitions for improved and semi-improved grassland (Olsen P and annual pasture yield) offer clear values that can be used as classification thresholds. The main criteria for 'high producing grasslands' are summarised as:

- Sown pastures. Excludes native grasslands and naturalised (adventive) pastures. Usually cultivatable land that can undergo 'pasture renewal'.
- High fertility (e.g. optimal Olsen P).
- High annual yields (e.g. >10 t DM ha^{-1} yr^{-1}) and high vigour.
- More common to rotational rather than extensive grazing management systems.
- Introduced grass and legume species (exotic), particularly annual ryegrasses, perennial ryegrass, white clover, and lucerne.
- Widespread in more favourable growing environments, particularly lowlands with few limitations regarding climate, soils, and moisture.
- Includes irrigated pasture.
- Common to intensive land uses with rotational grazing systems (e.g. dairy).

3 Pasture yield modelling feasibility

Differentiation of grassland into high or low producing classes is readily achieved when production levels can be estimated and class break thresholds have been established. All preceding definitions other than that used in LUM refer to production as a criterion, and 2nd Edition NZLRI definitions provide clear thresholds of < or >10,000 kg DM ha^{-1} as potential class breaks. Methods are available to broadly estimate pasture yield patterns either by modelling (e.g. Fig. 1) or disaggregation of stock numbers from farm databases using feed-demand relationships.

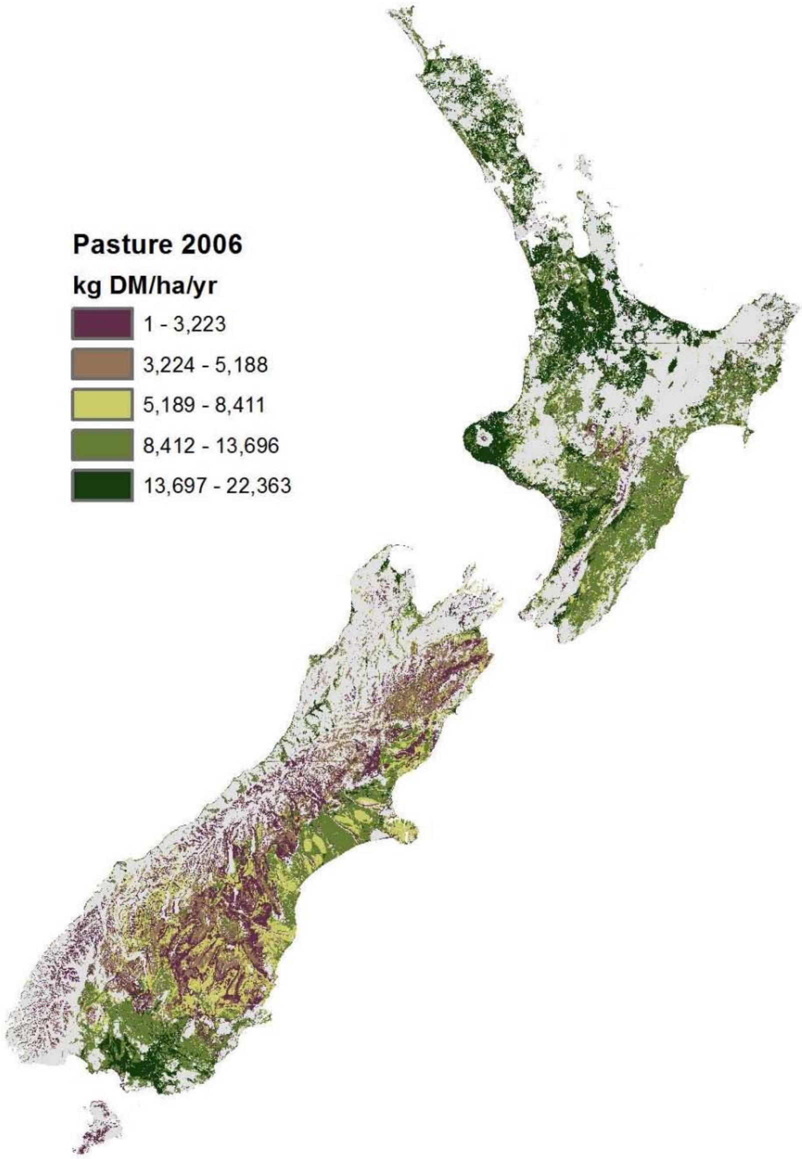


Figure 1 Example of spatial pasture production modelling. Based on Moir et al. (2000) using daily soil water balance modelled at 100-m resolution. A uniform level of land development and management is assumed.

A review was commissioned to evaluate pasture yield modelling and the use of thresholds as a potential pathway for improved classification of high and low producing grassland (Appendix 1). We also undertook exploratory modelling using the climate-fertility driven method of Moir et al. (2000) and the decision tree method of Zhang et al. (2009). Our key conclusions are:

- Rainfall, soil temperature, and solar radiation explain the majority of the variation in NZ's pasture production. Soil characteristics are also key determinants. Both the models and data are available to generate national pasture yield estimates based on environmental inputs (e.g. Fig. 1).
- However, inferences drawn from modelling of environmental data alone may be misleading because land improvement (e.g. fertiliser use, irrigation, artificial drainage) and grazing management have a major influence on actual levels of pasture production. Models that factor in improvements and management are available but tend to be more demanding in terms of parametrisation and processing, and the data inputs that are needed to drive a national modelling exercise are sparse, incomplete, or completely unavailable.
- Levels of pasture production vary between years. At a threshold of 10 t DM ha^{-1} yr^{-1}, a classification of 'high' or 'low' producing can change between years for some pastures (see Figure in Appendix 1). Long-term average modelling would be required (30–40 years of data). Historical data describing farm improvement and management are not available for nationwide modelling.
- There are limited long-term pasture production datasets available. Only 35 datasets were identified, most of which are site data. Validation opportunities would therefore be limited, and would need to accommodate scale differences (i.e. national model outputs vs. data from small trial plots).
- Pastures with traditional 'low producing' species can be managed to produce >10 t DM ha^{-1} yr^{-1}, and conversely, 'high producing' species can produce below a 10 t DM ha^{-1} yr^{-1} threshold.

A simulation modelling approach may still have potential, but we conclude a robust simulation modelling exercise to be beyond the resource and time limits available to this project.

4 Improved grassland classification using fuzzy logic

4.1 Introduction

Fuzzy logic is an organised method for dealing with imprecise information and data. While 'fuzzy' may imply a lack of seriousness, the method itself represents its own branch of mathematics broadly similar to ideas of probability and uncertainty, but different in terms of method and conceptual representation.

The Merriam-Webster dictionary (1997) defines fuzzy logic as a system of logic in which a statement can be true (value = 1.0), false (value = 0.0), or any of a continuum of values in-between. It is therefore a form of many-value logic, in contrast to ideas of Boolean logic where statements are either true or false (0 or 1). Truth of a fuzzy statement or proposition is a matter of degree. For example, the statement "the patient is young" is true to some degree. The lower the age of the patient (measured in years) the more the sentence is true (example adapted from Phuong & Kreinovich 2000).

Fuzzy logic is extensively used in research, computing, and engineering. At least 26 research journals are dedicated to the topic, with upwards of 89,000 published works and over 20,000 patents produced by 2013 (Singh et al. 2013). Further, fuzzy logic is widely used in practical applications such as controls for vacuum cleaners, washing machines, digital cameras, antiskid brakes, air conditions, and vehicle transmissions. Fuzzy logic methods have also been developed for geographical analysis, especially for expert-based applications, cluster analysis, and fuzzy neural nets (Kemp 2008). Of particular relevance here, are methods that can represent linguistic variables (e.g. 'high', 'low') as numerical fuzzy sets.

4.2 Aim

The aim is to develop and implement a fuzzy-logic based classification of high and low producing grassland at the national scale for the 2008, 2012, and 2016 LUM reporting years.

4.3 Methods

The definitions and criteria reviewed in Section 2 are rephrased into statements (as precursors to semantic statements). Analyses and review is undertaken to identify appropriate thresholds and functions for developing fuzzy membership relationships, which in turn are applied to spatial datasets to transform them into fuzzy membership classes (with values of 0.0 to 1.0). This step is sometimes referred to as fuzzification (Fig. 2). Choice of fuzzy memberships was influenced both by criteria available from definitions, and by the availability of appropriate national datasets.

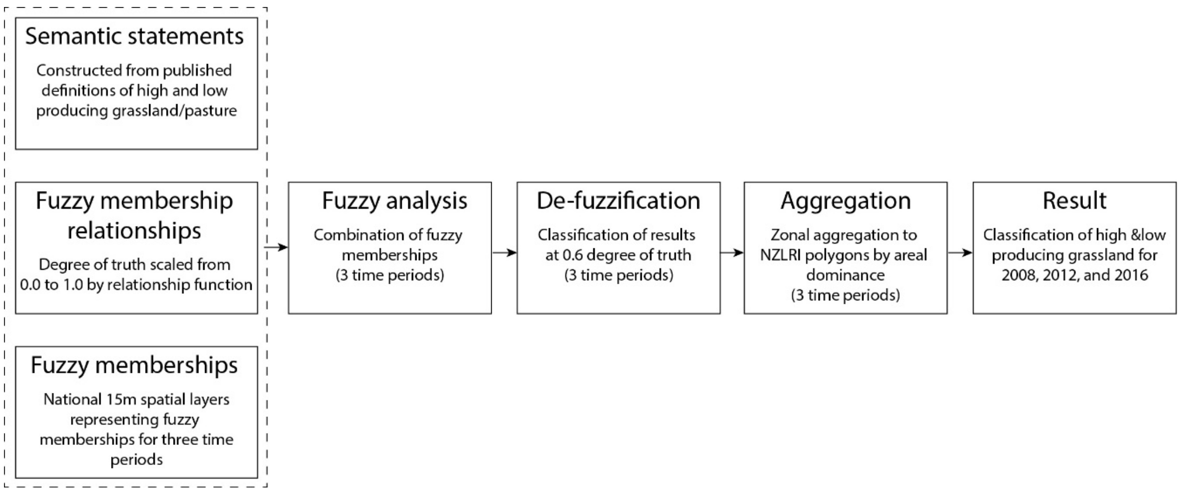


Figure 2 Overview of the analysis process.

Twelve fuzzy memberships are generated (to be discussed under their own headings). These are combined within an Esri ArcGIS model to produce three intermediate fuzzy members that represent the 'degree of truth' of being high producing grassland according to *environmental inputs*, *land use inputs*, and *previous land cover* (Fig. 3). All three intermediary layers are further combined to generate the penultimate result. Irrigation is proposed as an absolute truth and is thus assigned a fuzzy value of 1 (i.e. if irrigated pasture, then the class is always high producing). "Protected land" (QEII covenants, NWR Kawenta, DOC managed estate, land protected under other statutory protection, and land not otherwise used for agricultural purposes) is assumed to be low producing grassland at the national modelling scale.

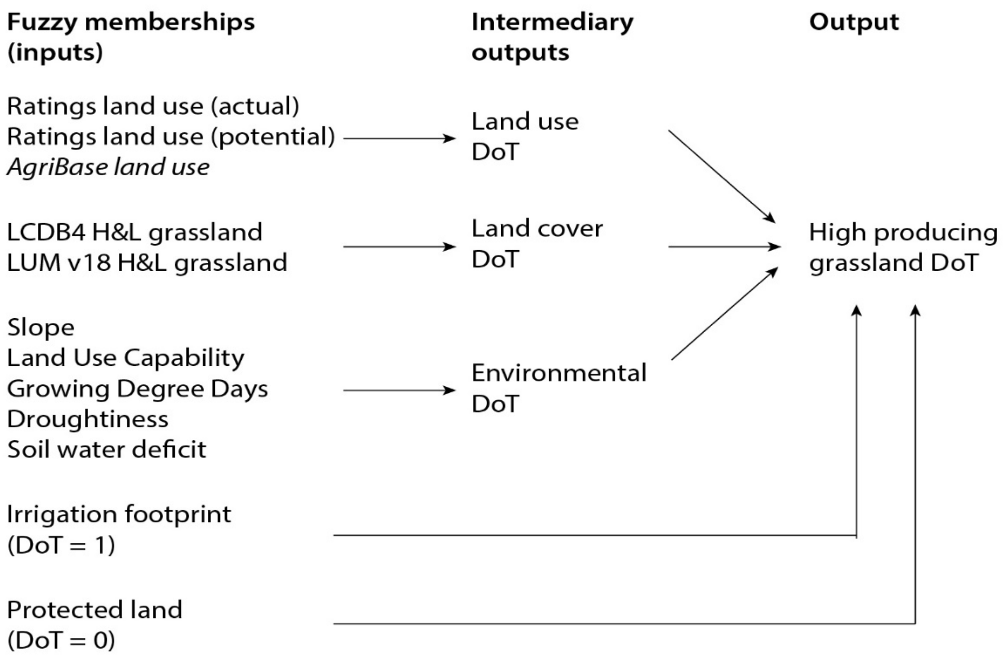


Figure 3 Inputs and outputs of the fuzzy logic analysis component. DoT refers to 'degree of truth'. AgriBase land use (italicised) included for evaluation.

In the final 'degrees of truth' layer, values closer to 0.0 are less likely (or are less true) to be areas of high producing pasture than areas with values closer to 1.0. The final classification as high or low producing pasture is achieved by reclassification to a threshold value of 0.6 (<0.6 less likely to be high producing pasture than >0.6). A >0.6 value is used as it has higher confidence of being high producing than 0.5, and manual inspection of the classes over aerial photography supported the slightly higher threshold.

When the output layer was vectorised a large number of irregular and small polygons were generated. This was attributed to fine detail added by the slope fuzzy member (derived from a 15m digital elevation model). To avoid creating an unnecessarily complex and large LUM dataset, the fuzzy analysis output was aggregated by areal dominance into NZLRI polygons. If an NZLRI polygon contained >80% of (fuzzy) high producing pasture, then the polygon was classed as high producing grassland. This method retains the same unit structure for managed grassland used in previous editions of LUM, including the use of dominance to determine whole polygon class.

No weighting adjustment is performed for any fuzzy memberships, but an implicit level of weighting has been included as fuzzy membership relationships were generated. The ESRI fuzzy gamma function is used to combine membership classes, whereby the gamma value is adjusted according to the number of input layers used. In this way, any combination of values at the 0.5 degree of truth will always return a value of 0.5.

The AgriBase is a national farm dataset that provides a spatial representation of land use. It is, however, a commercial dataset that costs money and carries licensing restrictions. We evaluate the implications of removing the AgriBase from the analysis simply by omitting it from the model.

A basic farm type classification is added to the final managed grassland classes. Farm classes are limited to pastoral "dairy" and a single "sheep, beef, deer, and other" class. Adding more farm classes had the potential to result in a large LUM dataset with complex polygons. Narrow corridors between farms of the same class (such as roads or streams) were removed to further promote large single-class polygons.

All processing was undertaken in a raster environment at 15m resolution using ArcGIS 10.2.1. The analysis was applied to the full area of NZ and subsequently clipped to the extent of managed grassland represented in LUM 2012 (version 18) for evaluation. This differs from the new forthcoming LUM managed grasslands extent developed by Newsome et al. (2018). Areas reported in the results section of this report are therefore for comparison only, and apply only to this report.

4.3.1 Previous land covers

Statement: *High producing pastures are more likely to be present in areas that have previously been mapped as having high producing pastures*.

This is not an absolute truth as it is possible that high producing pastures can revert to low producing pastures. However, with ongoing intensification of land use, we would argue that it is more likely that a greater proportion of low-producing is being converted to high producing rather than the other way around. For example, between 2007 and 2017 the Agricultural Production Census reports a decrease of 568,000 hectares of tussock and danthonia grasslands (i.e. particularly low producing grassland species) within common pastoral farm types (sheep, beef, deer, and horses).

Two fuzzy membership classes are generated for previous land covers using high production grassland classes from the LUM v18 and LCDB4 v4.1. High producing is assigned a 'degree of truth' (DoT) value of 1, and an indeterminate value of 0.5 is assigned to all other classes. Previous landcover fuzzy members were created for each year represented in both the LUM v18 and LCDB4 v4.1.

4.3.2 Slope

Statement: *Pasture production decreases with increasing slope. Low producing grassland is common to steep hill country throughout NZ, often intermixed with small areas of high production on more accessible (flat) and more fertile sites (stock camps).*

A number of hill country pasture trials have demonstrated reduced pasture yields on steep slopes relative to easy slopes (e.g. Gillingham 1974; Dodd et al. 2003; Morton et al. 2005; Bretherton et al. 2010).

The slope effect is implicit in the NZLRI database with the relationship between slope category and Average Carrying Capacity (CCAV). CCAV represents the average farmer stocking rate (as stock units per hectare) estimated at the time of NZLRI preparation. Here we use it as a proxy for feed demand and pasture production potential. For example, based on historical values, 1 stock unit requires 550 kg DM ha^{-1} yr^{-1} (Coop 1965) which at an assumed 70% utilisation equates to a necessary pasture yield of 785 kg DM ha^{-1} yr^{-1} to sustain one stock unit.

The relationship between NZLRI slope categories and mean CCAV (and pasture yield by proxy) is approximately sigmoidal in shape (red dotted line in Fig. 4). Midpoint of the curve occurs at 25°, which is also the commonly accepted threshold for steep-land.

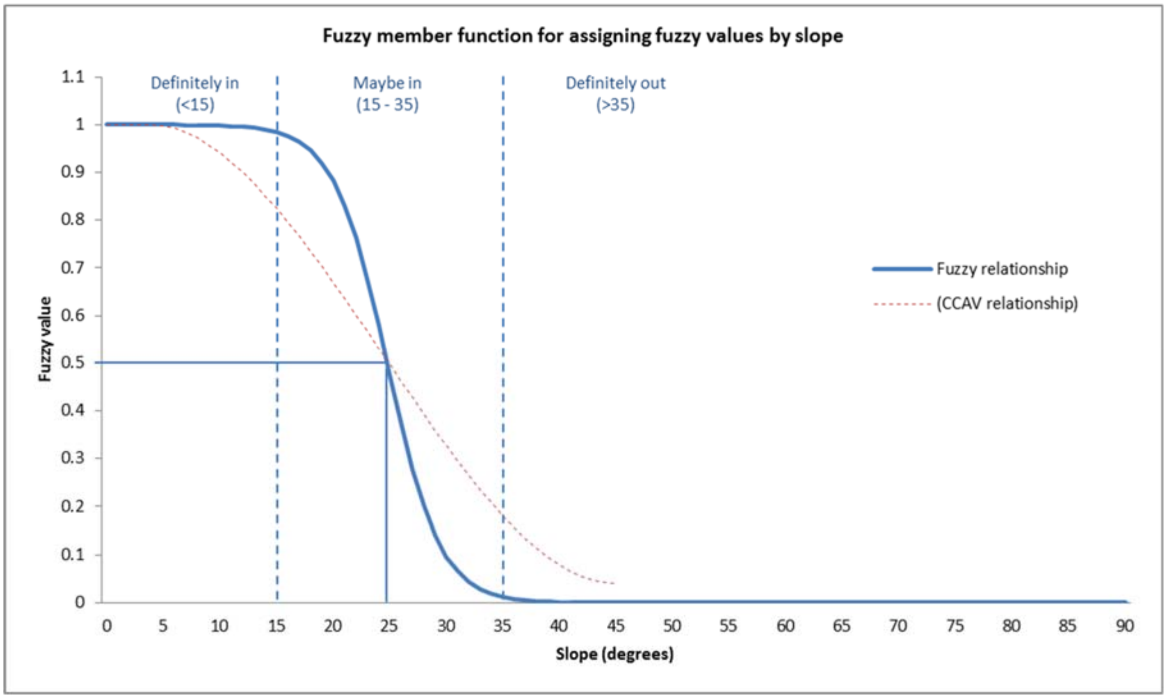


Figure 4 Fuzzy member relationship for slope (blue sigmoid curve). NZLRI slope vs. CCAV smoothed relationship as the red dotted line.

High producing pasture is frequently described or defined as being sown pasture (Section 2). Land that is flat is considered more feasible to sow than land that is steep. We use *commonly recognised critical slopes for specified activities* (Lynn et al. 2009) to determine key thresholds to accommodate 'sown pasture', whereby slopes <15 are interpreted to have few limitations and thus have relatively high likelihood of being (sown) high producing pasture. Slopes 15°–25° have a more favourable potential than slopes 25°–35°, while the activity of sowing and the presence of high producing pasture is least likely on slopes >35°. This produces a more strongly sigmoidal fuzzy membership relationship (Fig. 4).

The slope fuzzy membership relationship is applied to slope calculated from the Landcare Research 15m Digital Elevation Model.

4.3.3 Land use

Statement: *High producing grasslands are grazed for intensive wool, lamb, beef, dairy, and deer. Low producing grasslands are more typically grazed for extensive wool, sheep-meat and beef production. Intensively grazed farmland requires high annual pasture yields (>10 t DM/ha/yr) to support high stocking rates. Extensively grazed farmland requires lower pasture yields (<8 t DM/ha/yr) because of lower livestock feed requirements.*

Intensive pastoral land uses are characterised as having high feed demands that can only be met by high pasture yields. For example, for the average NZ dairy farm running 2.8 cows per ha and producing 381 kg of milk solids per cow (LIC & DairyNZ 2017) at an assumed live weight of 450 kg per cow, feed demand for a pasture only diet (with an energy content of 11 MJME) would broadly equate to 14.5 t DM ha^{-1} yr^{-1} (based on conversions in Trafford and Trafford, 2011) or an annual pasture yield of 17 t DM ha^{-1} yr^{-1} at a high 85% utilisation rate. While imported feeds are commonly used to supplement dairy production, such feeds are considerably more expensive than pasture, and we would expect that farmers investing in supplements would already be realising near optimal levels of pasture production.

A 2018 version of the AgriBase was examined to explore the relationship between farm type and potential pasture demand (as stocking rate per hectare). Agribase livestock numbers were converted to whole-farm stocking rates according to the method of Manderson et al. (2018). Results confirm that some land uses are more intensive than others, with key pastoral uses following an intensity rank of Dairy cattle farming > Beef cattle farming > Deer farming > Mixed Sheep and Beef farming > Sheep farming. Mean stocking rate for dairy was 18.5 su ha^{-1} yr^{-1} (~2.6 cows ha^{-1} at a stock unit equivalent of 7 su per cow) which is similar to the national mean of 2.8 cows ha^{-1} reported by LIC & DairyNZ (2017).

Potential pasture yield for farm types was estimated by calculating feed demand from stocking rate (Section 4.3.2) updated according to changes in mean ewe live-weight and lambing percent reported in the NZ Greenhouse Gas Inventory (MfE 2018) and conversion factors reported in Parker (1998). The updated 2016 feed demand of 1 stock unit is estimated as 640 kg DM ha^{-1} yr^{-1} (cf. 550 kg DM ha^{-1} yr^{-1} for 1965).

Lynn et al.'s (2009) high and low producing thresholds for annual pasture production were translated into equivalent stocking rate thresholds using the updated feed demand value (Table 6), and the thresholds were used to build a stocking rate fuzzy membership relationship (Fig. 5).

Table 6 Pasture yield thresholds translated to stocking rate equivalents

Pasture threshold (kg DM ha^{-1} yr^{-1})	*Semantic class*	*Equivalent stocking rate threshold (1 su requiring 640 kg DM ha^{-1} yr^{-1} at 70% util.)*
6000	Is definitely low producing	6.6
8000	Is likely low producing	8.7
10000	Is likely high producing	10.9
12000	Is definitely high producing	13.1

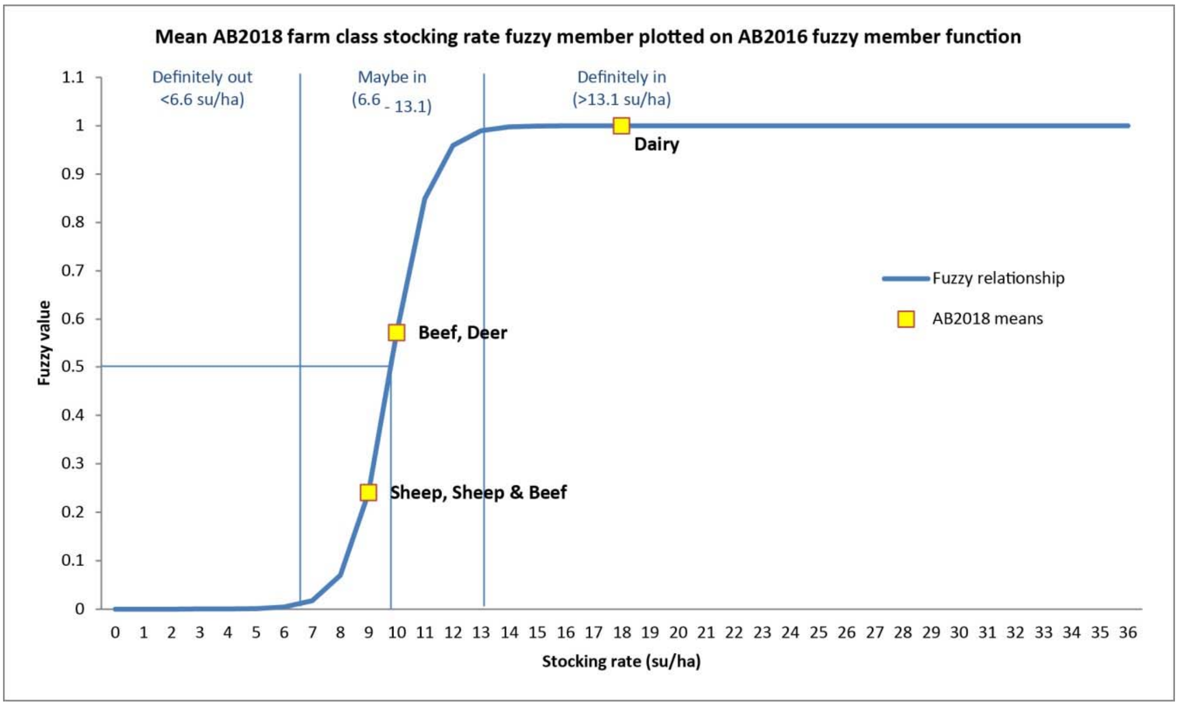


Figure 5 Fuzzy member relationship for stocking rate, used to develop degrees of truth values for individual land uses (farm types). Rounded stocking rates means of key AgriBase pastoral farming types plotted as points for context.

A stocking rate fuzzy membership layer was not generated because of AgriBase licensing considerations, and the high level of data cleaning and preparation that can be necessary with the AgriBase (e.g. see Manderson et al. 2018). Further, other national farm type datasets are available that contain no livestock or intensity-related attributes. Instead, degrees of truth were assigned to individual farm types (or land uses) based on the previously described analysis of AgriBase stocking rates. Look-up tables were generated and used to create three fuzzy membership layers for *AgriBase land use*, *ratings land use (actual)*, and *ratings land use (potential)*. AgriBase land use was included to evaluate the implication of not using it in the analysis.

Ratings land use data are available for every legal property parcel in NZ. As part of the valuation process, each parcel is classed with both an *actual property use*, and a *property category* defined as “the highest and best use, or the use for which the property would be sold given the economic conditions prevailing at the effective date of valuation” (LINZ

2010, p. 60). Valuations take place every three years for ratings purposes, and Corelogic NZ manages NZ's valuation data. Ratings land use data for rural classes were sourced by MfE from Corelogic for 2008, 2013, and 2016. *Actual property use* was used to construct the *ratings land use (actual)* fuzzy membership layer, and the *property category* was used to build the *ratings land use (potential)* layer.

4.3.4 NZLRI Land Use Capability

Statement: *High producing grasslands are most likely associated with higher capability land.*

The NZLRI inventory contains a classification of Land Use Capability (LUC) that effectively rates land according to its production potential for agriculture and other uses. LUC class 1 land is highly versatile, productive, and suitable for a wide range of uses, while LUC class 8 land is not suitable for agriculture.

Several studies have reported pasture production yields by LUC (Barlow 1985; Cichota et al. 2014; Vogler et al. 2016; Hicks & Curran-Cournane 2017). Further, NZLRI CCAV was converted to a feed demand and potential pasture yield (Section 4.3.2), and summarised to produce LUC class means. All available estimates of pasture yield (observed, modelled, and calculated) by LUC class were used to identify the fuzzy membership relationship for LUC class (Fig. 6). Fuzzy membership thresholds are based on high and low pasture production thresholds from Lynn et al. (2009), and are applied to NZLRI polygons at the LUC class level, which is subsequently rasterised to 15m resolution as the LUC fuzzy membership layer.

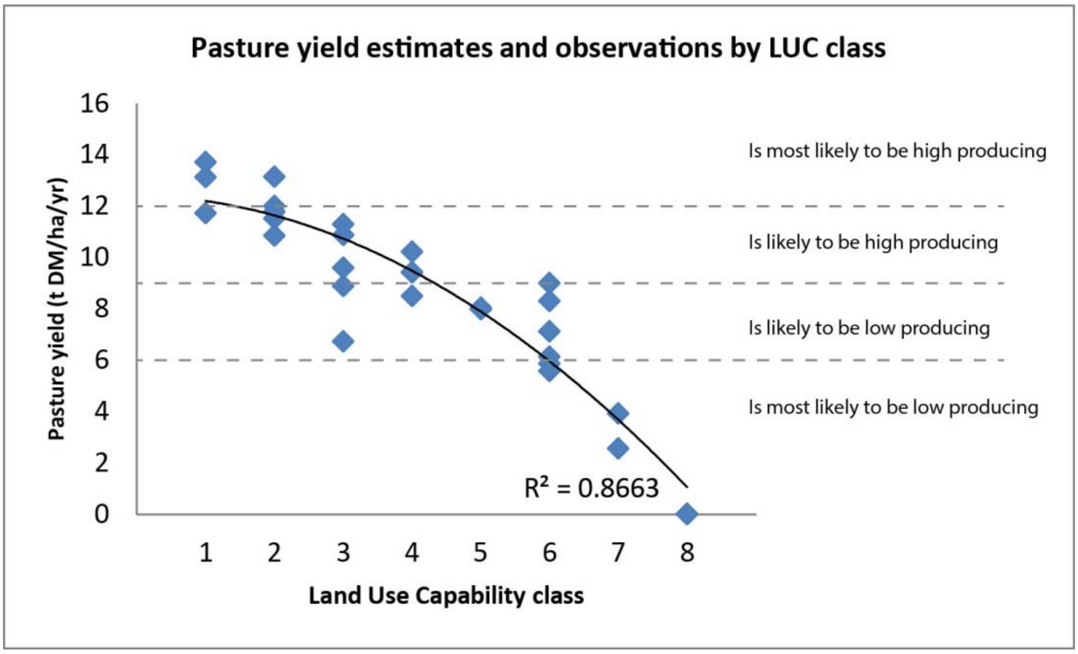


Figure 6 Relationship between estimates of annual pasture yield and NZLRI Land Use Capability (LUC) class drawn from pasture yield observations, modelling, and analysis of NZLRI CCAV.

4.3.5 Moisture deficit and soil-drought risk

Statement: *High producing pasture is less likely in areas with soil-moisture deficits or droughtiness (or areas that 'brown off' in summer). Examples include dry hill country in eastern Hawkes Bay, Marlborough, Canterbury, and Northland.*

Water is essential for plant growth. Periods of moisture deficiency will reduce annual yields. Many of the lower production grass species are better adapted to dryland conditions. Two fuzzy membership layers are developed. First, a climate-driven moisture deficit fuzzy member is created based on Land Environments NZ (LENZ) moisture deficit (Leathwick et al. 2002) in conjunction with recognised dryland landscapes of NZ (Rogers et al. 2005). Second, soil drought risk is mapped by applying the S-Map drought vulnerability classification to the Fundamental Soils Layers, with degree of truth values assigned directly by the level of risk (Table 7).

Table 7 S-Map soil droughtiness vulnerability

S-Map vulnerability class	*Profile Available Water (PAW) to 1m*	*Degree of truth*
High risk	<=60 mm	0.25
Moderate risk	60–120 mm	0.75
Low risk	>=120 mm	0.99

4.3.6 Growing degree days

Statement: *High producing pasture is widespread in the NZ lowlands (including hill country), and less widespread in the montane areas. Low producing pasture associates with shorter growing seasons, especially in the South Island. Extensively grazed low-producing grasslands are commonly found in NZ high country.*

We use growing degree days at a 5°C base (GDD_5) to represent the effect of altitude, temperature, and length of growing season. A 5°C base is often accepted as the cool temperature threshold for the growth of common temperate grasses such as perennial ryegrass (Hutchinson et al. 2000).

High producing pasture is least likely to occur where GDD_5 are <1,500. This includes alpine areas (GDD_5 <500) and much of the NZ high country. For example, dryland pasture production on undeveloped Mackenzie soils in the Upper Waitaki Basin ranges from 1 to 3 t DM ha^{-1} yr^{-1} (Greenwood & Paton 1985), while trials at Poolburn (1,495 GDD_5) for dryland pasture reported an average annual yield of 2.8 t DM ha^{-1} yr^{-1} over 10 years (Radcliffe & Cossens 1974).

Low producing rather than high producing grassland is more likely to occur in the 1500–1700 GDD_5 band. We base this on the distribution of GGD_5 means for all dairy farm parcels from both ratings data and the AgriBase (Fig. 7), and an assumption that the majority of dairy farms will qualify as having high producing pasture. AgriBase results for Southland were extracted for closer examination, as Southland has the lowest GDD average of all dairy regions. The 1500–1700 GDD_5 band falls within the lower quartile of GDDs for all dairy farms in NZ (AB2018 and CL2016), and only the lower outliers are implicated for Southland dairy farms.

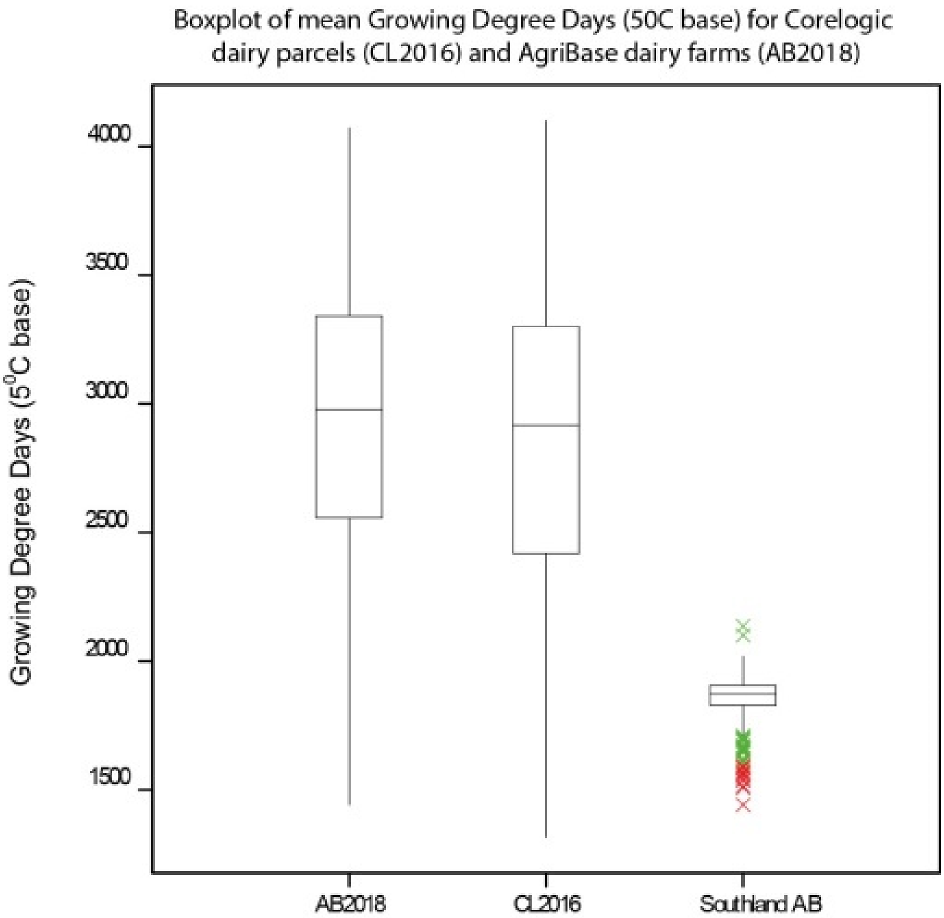


Figure 7 Boxplot distributions of mean growing degree days for each dairy parcel in the AgriBase (AB2018), ratings data (CL2016), and the AgriBase for Southland dairy farms (Southland AB).

High producing grassland is more likely in the 1700–1830 GDD_5 range. This range captures the lower 25% of Southland dairy farms. Greater than 1830 GDD_5 is proposed as the point where GDDs effectively becomes non-limiting. For context, Hutchinson et al. (2000) reported 12 t DM ha^{-1} yr^{-1} annual yield for Winton Research Farm in Southland, which we calculated as having a mean GDD_5 of 1914.

A sigmoid shaped relationship was developed to capture the GDD_5 threshold values as a fuzzy membership relation (Fig. 8).

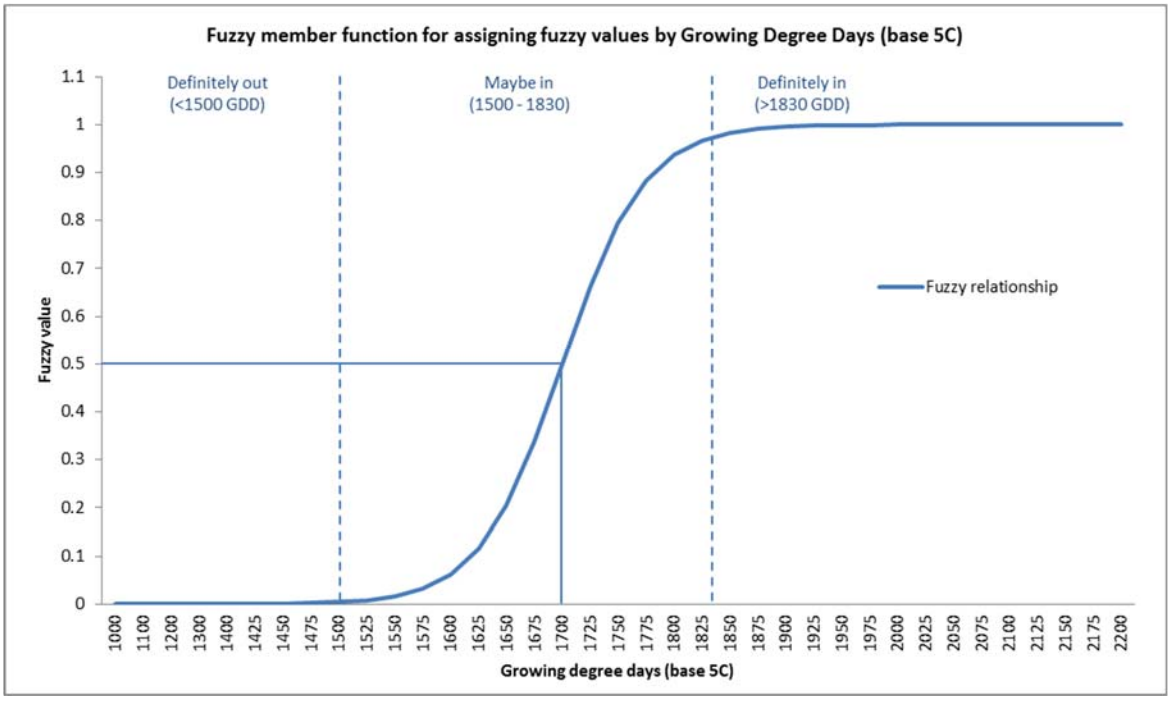


Figure 8 Fuzzy membership relationship for Growing Degree Days.

4.3.7 Irrigation

Statement: *Grassland under irrigation is expected to be high producing pasture*.

The proposition that all grassland under irrigation is high producing pasture is not an absolute truth. Trials in hard high-country environments report irrigated yields less 8–10 t DM ha^{-1} yr^{-1} (e.g. Radcliffe & Cossens 1974). However, yields are always significantly higher than the unirrigated controls, and developments associated with irrigation investment would likely satisfy other criteria of high producing pastures (e.g. vigour, pasture species, soil fertility).

Irrigation footprints mapped by Dark et al. (2017) for 2016 were assigned a fuzzy membership value of 1, and rasterised to 15m resolution as the irrigation fuzzy membership layer. This was added late in the analysis via a Boolean conditional statement.

4.3.8 'Protected areas' and unfarmed grassland

Statement: *Grassland under protected areas is most likely to be low producing grassland.*

High producing pastures are maintained through pasture renewal, fertiliser inputs, and grazing management. Land that is not used for agriculture is generally less likely to receive the same level of inputs and management, and is thus less likely to be high producing grassland. Such areas include transport curtilage, grassland within conservation areas managed by the Department of Conservation (especially tussock grasslands), retired or redundant areas of farms, or grassland areas under a statutory protection (i.e. agricultural practices are not permitted).

'Protected areas' layers were generated for each time period based on the Protected Areas Network New Zealand (PAN-NZ) method of Rutledge (2008), modified to extract legal parcels having common statutory protections recorded in Land Information NZ (LINZ) primary parcels and statutory use tables (cf. to the survey of councils' approach used by Rutledge et al.). For QEII and NWR protected areas, the most recent datasets were sourced (NWR 2018; QEII 2018) and divided into target time periods according to date attributes. A similar exercise was invalid for Department of Conservation (DOC) Public Conservation Areas (DOC 2018) because the addition of new protection mechanisms can distort areas under legacy protection. Rather, archived datasets for each period were obtained from DOC through MfE.

The resulting vector layers were assigned a fuzzy membership value of 0 and rasterised to 15-m resolution.

4.3.9 Graphical summary of inputs

Graphical summary of the input layers as maps are provided as Figures 9–12. For interpretation, the darker the colour, the more likely high producing pasture will be present **for the individual fuzzy membership class**. Also note that the fuzzy logic analysis is implemented for all of NZ, as the final result is later masked to the managed grasslands window of LUM.

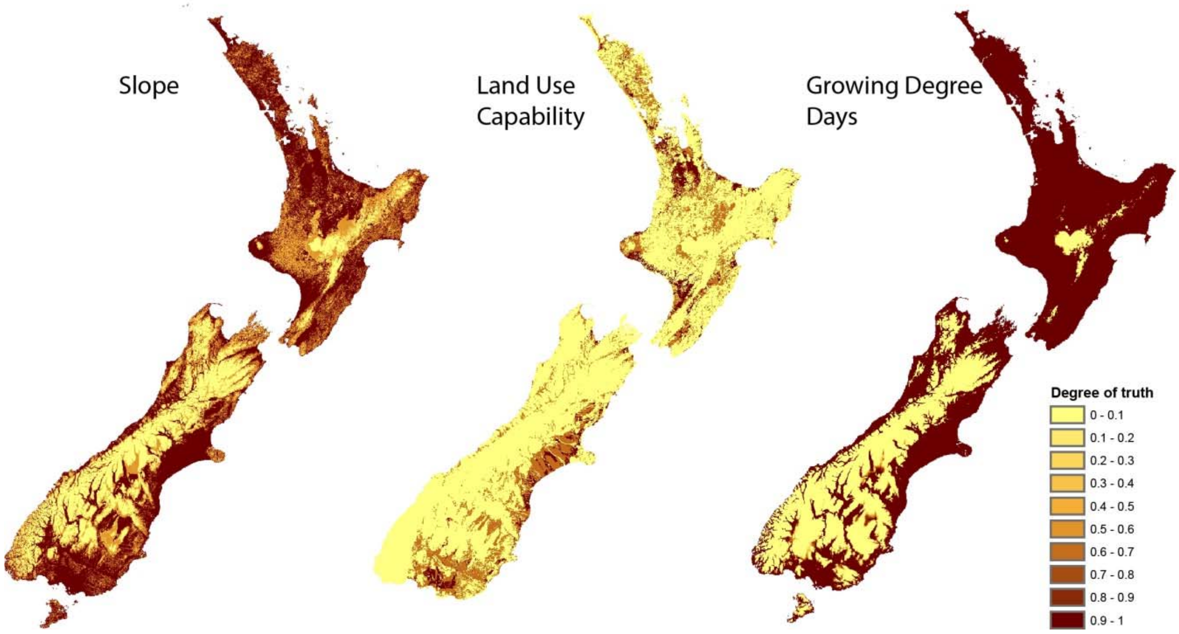


Figure 9 Maps of fuzzy memberships for slope, Land Use Capability, and Growing Degree Days.

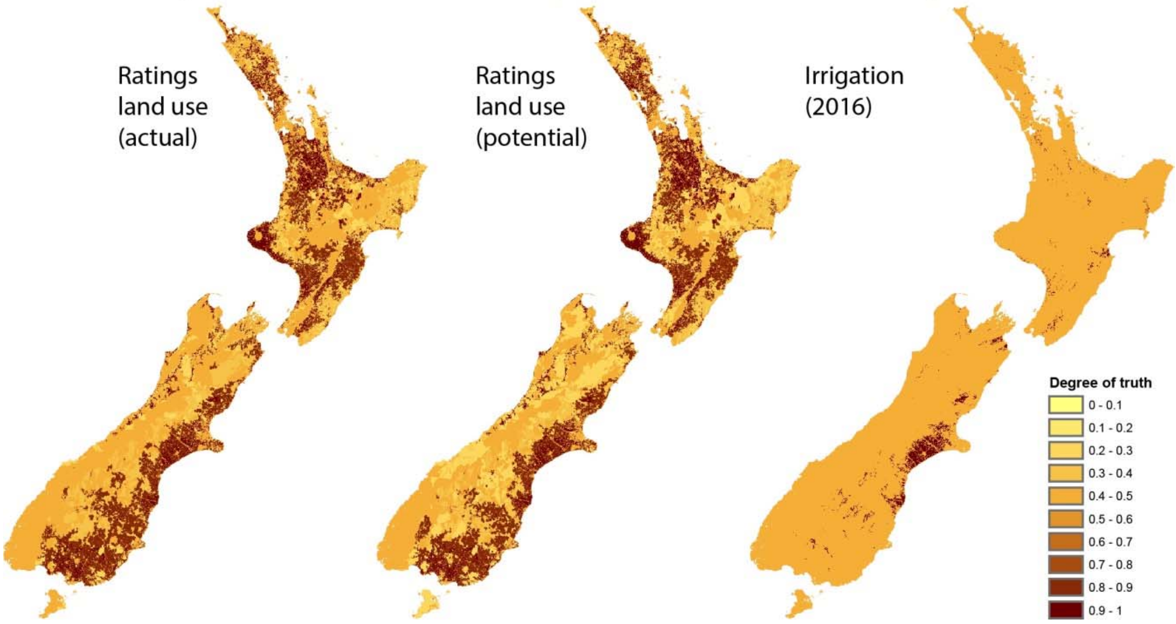


Figure 10 Maps of fuzzy memberships for Ratings land use (actual and potential), and irrigation.

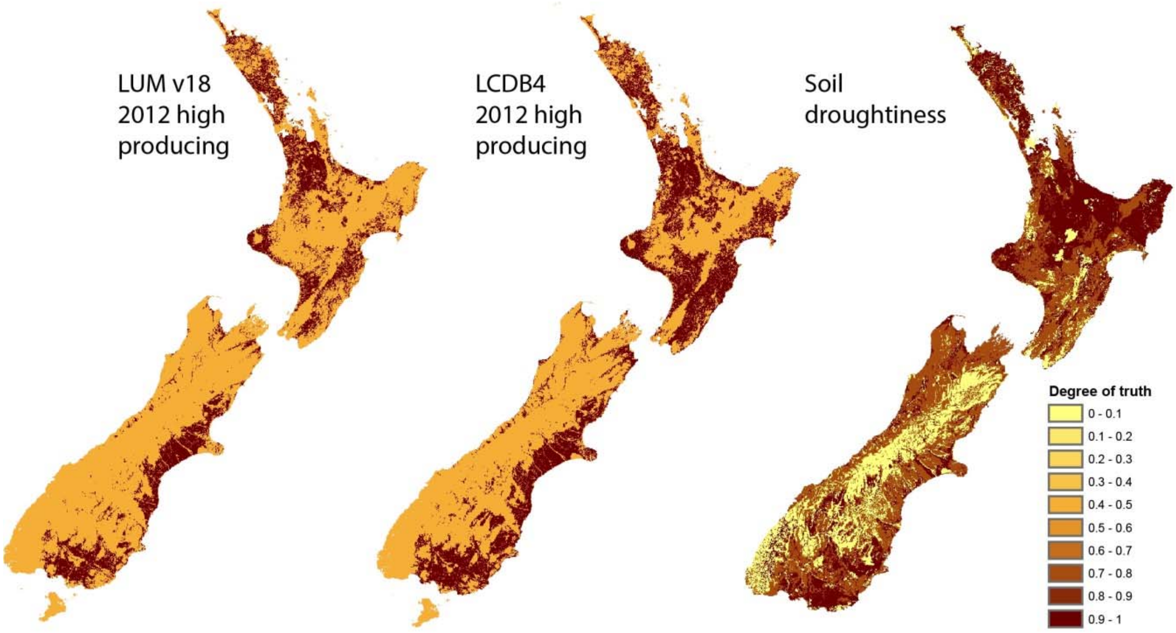


Figure 11 Maps of fuzzy memberships for previous grassland classifications (LUM v18 and LCDB 4.1), and soil droughtiness risk.

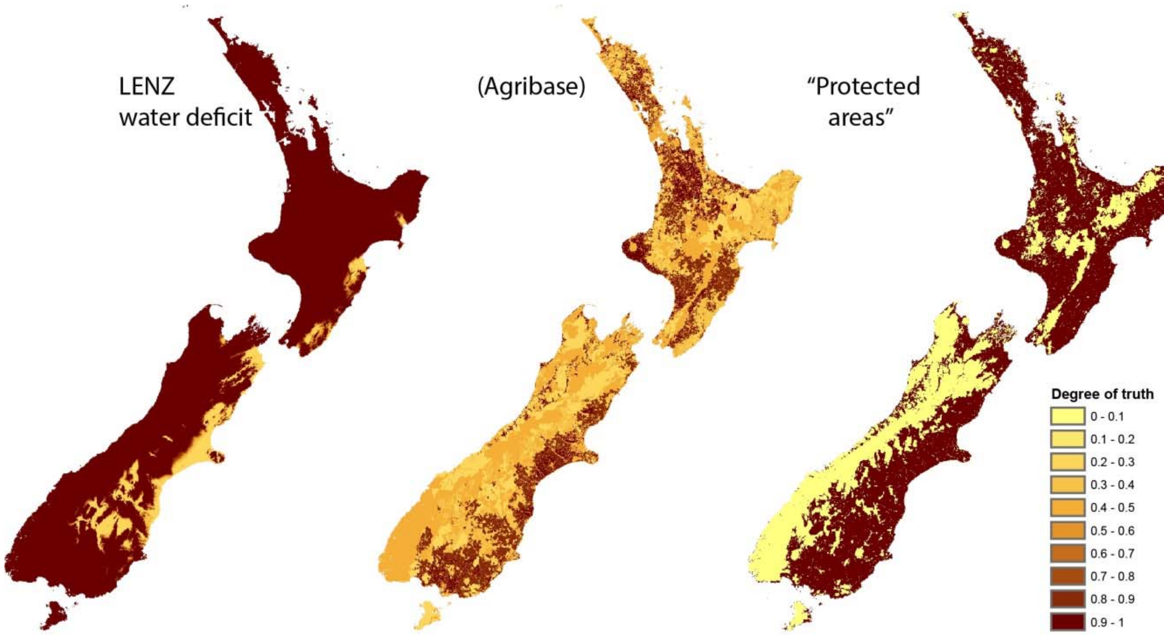


Figure 12 Maps of fuzzy memberships for LENZ water deficit, AgriBase land use, and protected areas.

4.4 Results

4.4.1 Intermediary fuzzy memberships

Three intermediary fuzzy memberships are produced (Fig. 13) representing the degree of truth (or likelihood) of high producing grassland being present according to environmental factors, land use, and previous land cover.

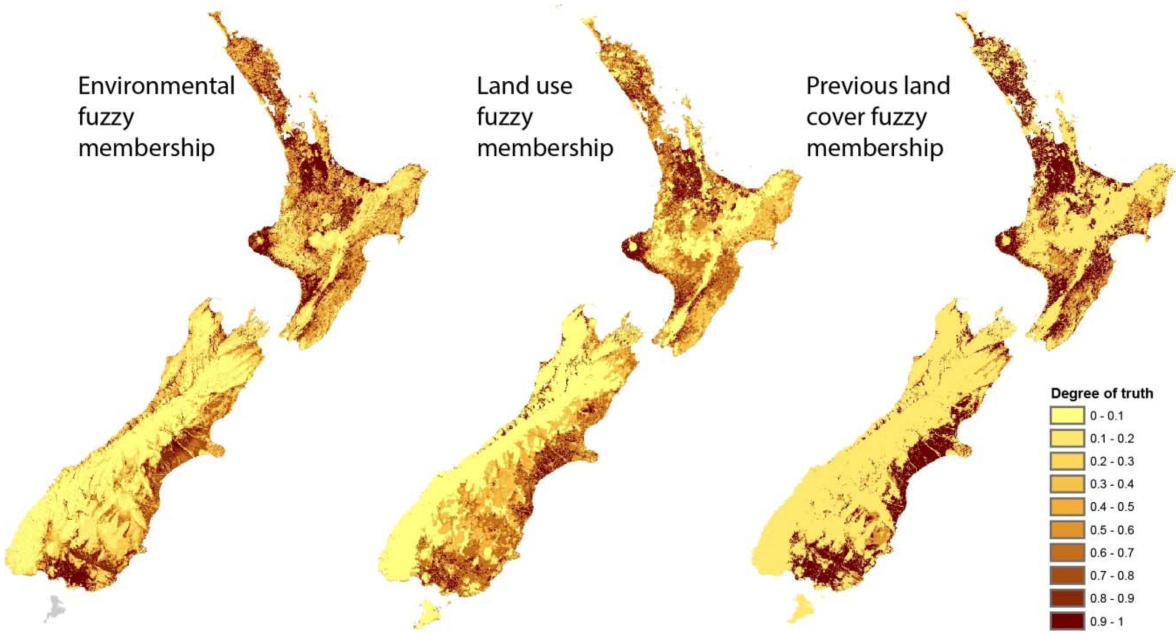


Figure 13 Maps of intermediary fuzzy memberships.

All three maps exhibit similarities regarding where the highest degrees of truth are expressed, likely reflecting an expectation that land use and land-cover types are influenced by differences in environment. Land use results for the High Country in the central South Island appear to contrast. We suspect data limitations as the cause, in that the land use datasets do not reliably differentiate extensive high country runs from lowland intensive sheep finishing and stud operations – both were classed as sheep farms and were assigned the same degree of truth value.

4.4.2 Final fuzzy logic layers for 2008, 2012, and 2016

Final output from the fuzzy logic analysis component is presented as maps for the three time periods (Fig. 14).

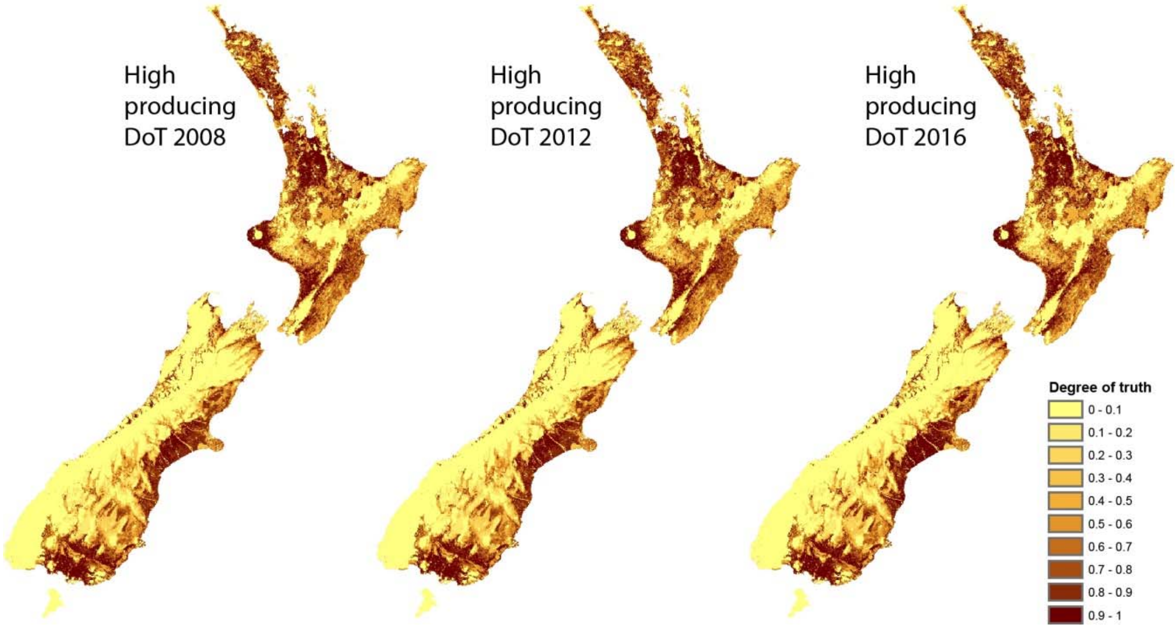


Figure 14 Final outputs from the fuzzy logic analysis for each of the three time periods (2008, 2012, 2016). DoT refers to 'degrees of truth'. The higher the DoT, the higher the likelihood of high producing grasslands.

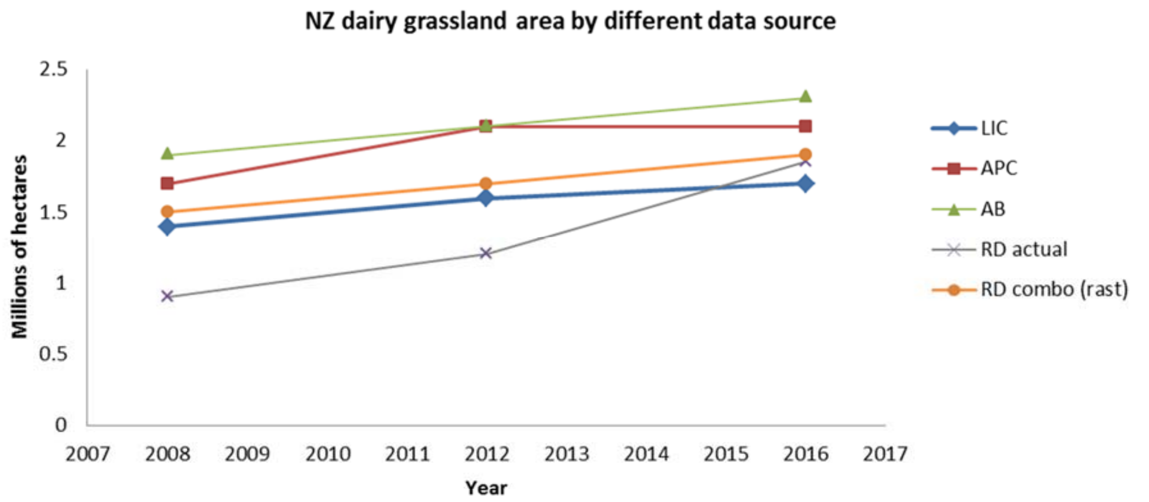
Little can be discerned between years at the scale of presentation. As an overall picture, the greatest potentials occur in expected regions such as the Waikato, Taranaki, Manawatu plains, Canterbury plains, and Southland lowlands, all of which have notably favourable growing environments and intensive land uses (particularly dairy).

4.4.3 Omitting the AgriBase fuzzy membership

The fuzzy analysis was implemented twice, once with, and once without the AgriBase fuzzy membership. Effect on the estimated area of high producing grassland was minor, resulting in a 1% difference in the proportion of high producing grassland at the 0.6 degree of truth (ranging from 0–2% within the 0.5 to 0.85 DoT band). The AgriBase fuzzy membership was retained however, as 3 layers of evidence are better than 2 (but note that the AgriBase was not used in the land use classification – Section 4.4.4).

4.4.4 Land use classification

The final classification of high and low producing grassland includes a simple land use classification of dairy, all other livestock farming, and not otherwise farmed grassland. Two key datasets are available for deriving a land use classification, including Ratings Data and the AgriBase, with the latter having strong use restrictions. The implications of using – or not using – a given dataset were evaluated for dairy land use. Total dairy grassland area has calculated for three methods/datasets, and plotted against reported total grassland areas from DairyNZ & LIC (2018) and Agricultural Production Census results for 2007, 2012, and 2017 (Fig. 15).



LIC = Livestock Improvement Corporation. Total effective dairy farm hectares reported by LIC & DairyNZ (2018) for the preceding season (e.g. 2007/08 is used for 2008).
APC = Agricultural Production Census. Total 'Grass land' for Dairy Cattle Farming (ANZSIC06) for the Agricultural Production Censuses 2007, 2012, 2017
AB = AgriBase dairy cattle farming (DAI) intersected with LUM managed grasslands. LUM 2012 extent is used for 2016.
RD = Ratings data. Actual dairy land use intersected with LUM managed grasslands. LUM 2012 extent is used for 2016.
RD combo (rast) = Actual dairy land use from ratings data, plus validated dairy land use from ratings data land use category. 'RD combo (rast)' is used in the final classification. Areas are summarised from the final raster outputs. LUM 2012 extent is used for all years.

Figure 15 NZ dairy grassland area by different data sources and methods.

There is considerable disagreement between methods/sources, possibly attributable to differences in 'dairy' definition. However, all methods/sources exhibit a trend of increasing dairy grassland area over time.

AgriBase dairy cattle farming (DAI) intersected with LUM v18 managed grasslands produces the highest estimates. Ratings data (*RD actual*) are notably lower, especially for 2008 and 2012. This is due to historical changes in the cadastre that make backward matching of parcels with tabulated valuation data difficult (if not impossible – historical parcel data were not always archived and are therefore unavailable).

The extent of dairy area represented by the ratings data was improved by including ratings data with a potential to be dairying, drawn from both the *Land use category class*, and successive years of actual land use classifications. Parcel classifications that could be validated from other sources (including the AgriBase) were retained and added to *RD* *actual* for years 2008 and 2012 to produce *RD combo (rast)*. This produces a mid-range estimate of dairy areas (Fig. 15) and is used in the final classification.

4.4.5 Final outputs

To fit within the unit classification structure of the LUM, the final fuzzy logic layers are summarised into NZLRI polygons by areal dominance, and assigned one of three broad land use classes (Fig. 16). Results for each reporting year are clipped to the boundary of LUM 2012 v18 for display, and for the calculation of areas (Table 8).

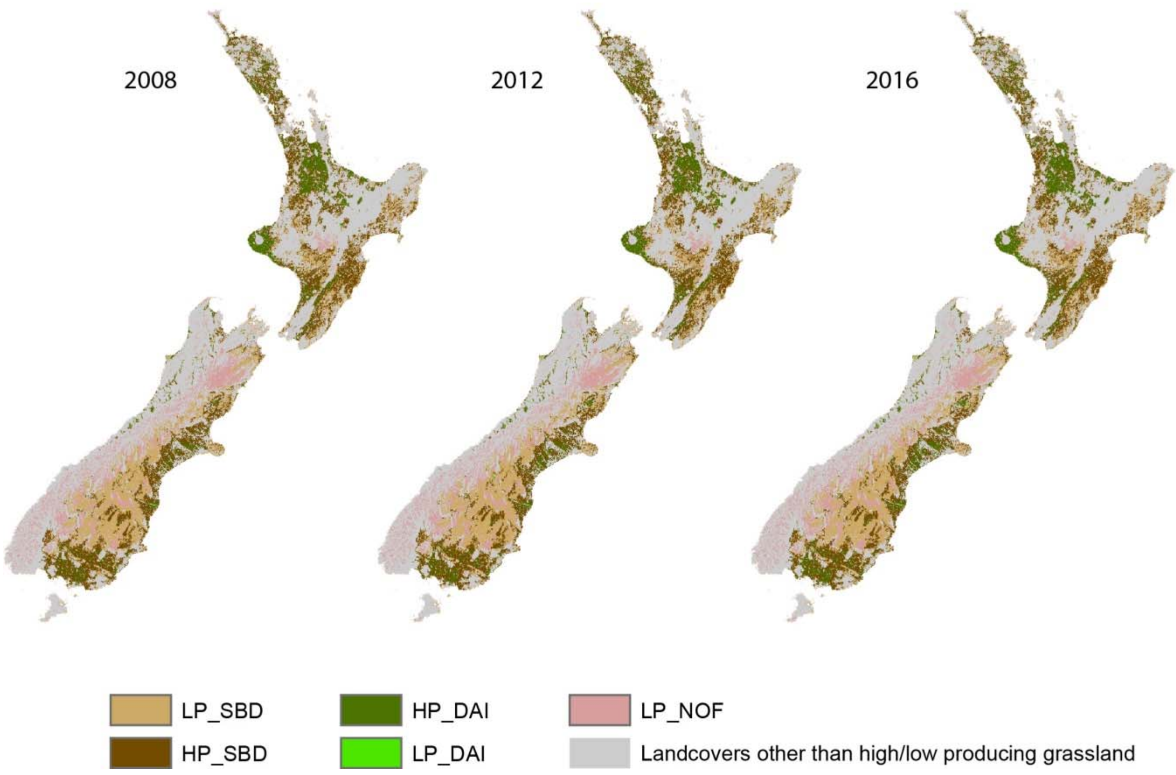


Figure 16 Fuzzy logic results aggregated by NZLRI units into high producing grassland (HP) and low producing grassland (LP) classes, further differentiated by a basic land use class of dairy (DAI), other livestock farming (SBD), and grassland not otherwise used for agriculture (NOF). Results clipped to LUM 2012 v18 managed grasslands for display.

Care is required with interpretation of the results – all outputs for all years are clipped to the managed grassland extent of 2012 represented by LUM v18. This does not account for changes in other land covers, such as conversion of forestry to pastoral, or afforestation of pastoral. With this in mind, the change in area between years is modest (Table 8), with high producing grassland increasing by 1% between 2008 and 2016. Similarly, dairy area increases and sheep/beef type land uses decrease, but the degree of change is minor (1–2%). However, for dairy at least, this rate and degree of change will be similar to that demonstrated in previous Figure 15 (because the same land use data sets are used).

Table 8 Summary of class areas with the LUM v18 2012 managed grassland footprint. Summarised at three class levels (grassland + land use, land use, grassland)

Class[1]	*Hectares*			*Percent*[2]		
	2008	2012	2016	2008	2012	2016
HP_DAI	1457161	1605564	1821097	11%	12%	14%
LP_DAI	54367	64838	72244	0.4%	0.5%	0.5%
HP_SBD	5230054	5089084	4920225	39%	38%	37%
LP_SBD	4350881	4322945	4219798	33%	33%	32%
LP_NOF	2196047	2206079	2255146	17%	17%	17%
DAI	1511528	1670402	1893341	11%	13%	14%
SBD	9580935	9412029	9140023	72%	71%	69%
NOF	2196047	2206079	2255146	17%	17%	17%
HP	6687215	6694648	6741322	50%	50%	51%
LP	6601295	6593862	6547188	50%	50%	49%
Total	13288510	13288510	13288510			

[1] HP = High producing grassland, LP = Low producing grassland, DAI = dairy, NOF = not otherwise used for farming, SBD = livestock farming other than dairy, mostly sheep, beef, and deer.

[2] Percent of total managed grassland area.

The estimated area of high producing grassland is lower than the LCDB4 equivalent, but higher than previous LUM estimates for the 2012 year (Table 9). This we regard as a positive result because the LCDB4 is thought to over-estimate high producing grassland, while previous LUM estimates are likely to under-estimate due to the NZLRI preparation period (effectively a 25-year window from 1973 to 1999, with most mapping undertaken before 1990).

Table 9 Comparison of 2012 managed grassland (LCDB 4.1, LUM v18, fuzzy logic method)

	LCDB4.1		*LUM v18*		*Fuzzy logic method*	
	Hectares	Percent	Hectares	Percent	Hectares	Percent
High producing	8844891	**67%**	5789397	**44%**	6694648	**50%**
Low producing[1]	4346112	33%	7499113	56%	6593862	50%
Total	13191003		13288510		13288510	

[1] LCDB Low producing includes Depleted Grassland, Low Producing Grassland, Tall Tussock Grassland, and Alpine Grass/Herbfield classes.

4.5 Discussion

The estimated change in high and low producing grassland area between years was not large. In part this is because we confine our summaries to the LUM 2012 v18 managed grasslands extent, thereby excluding the effect of significant land cover changes (e.g. deforestation to pasture). However, initially we also had an expectation that the degree of grassland change would likely be comparable to the degree of land use change. Dairy land use has increased; therefore, the area of high producing grassland should have similarly increased. This was not always the case, as many of the new areas of dairy already qualified has having high producing pasture, often captured as high degrees of truth in both the land cover and environment intermediary layers of evidence.

We also recognise that the margin of uncertainty between 'high and low producing' can be wide, and some locations can alternate between high or low depending on season and management (Section 3). Further, classification is a useful but blunt tool for representing reality, especially when only two classes are used. Uncertainty tends to be highest at the class breaks as values 'only just qualify' for a given class. For our analysis uncertainty is greatest at 0.6 DoT, with greater certainty as values shift toward 1 or 0 (Fig. 17).

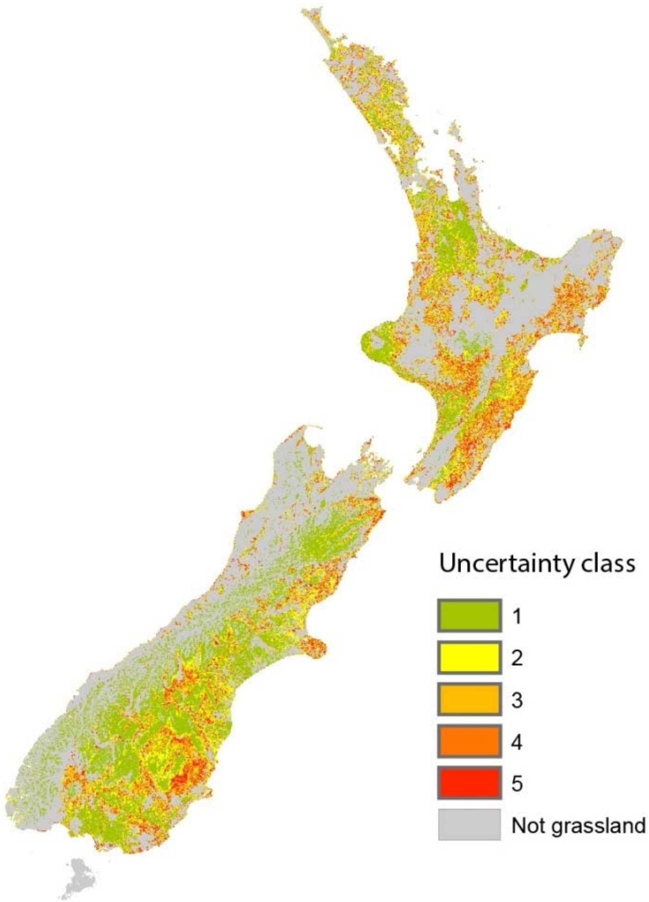


Figure 17 Uncertainty map. Classes represent distance from the class break value (DoT 0.6). Uncertainty class 5 has the highest uncertainty (DoT 0.55–0.65).

Fuzzy logic is a technique well suited for classifying grassland into high and low producing categories due to way grassland classes have been defined; the level of 'fuzziness' (or ambiguity) that is apparent around class margins; and because insufficient observed data are available – in both a temporal and spatial sense – for alternative options. However, as with all weights of evidence methods, fuzzy logic has its limitations, including a dependence on how well the evidence is translated to degrees of truth (i.e. the defensibility of the fuzzy relationship), and the degree of bias that may be introduced when combining layers of evidence (Coolbaugh & Bedell 2004). There remains scope to refine several of the fuzzy membership relationship functions developed in this project, especially through more strongly quantitative analytics if data are available (e.g. Bedell 2000), or through wider consultation with NZ expertise where qualitative-determination of functions is more appropriate.

Our greatest limiting factor, however, has been the availability and quality of spatial datasets necessary for a nationwide analysis, in particular, land use data, which are used to construct one of the three intermediary memberships, and thus have a strong influence on the final results (especially potential change from low to high producing grasslands). Disagreement between land use datasets was frequently encountered, and the cross-comparison disagreements in total dairying grassland were even apparent with census and industry data (Section 4.4.4). We are not confident that any one source is providing an accurate representation of land use in NZ.

All land use data used in this project could be improved with manual cleaning. For example, on occasion we encountered dairy farms classed into areas otherwise considered unsuitable for this use (e.g. hard hill country). Likewise, further work investigating the reliability of land use sub-classes (e.g. extensive vs intensive 'sheep farming') would improve the fuzzy logic framework. Access to the non-rural component of the ratings data would also have allowed for improved differentiation of high producing grassland within non-agricultural uses.

Simulation modelling of pasture yield is another avenue that could improve the framework. A long-term national estimate of <u>reference</u> pasture yield (similar in concept to Reference Crop Evaporation) would potentially be an improvement over the (intermediary) environment fuzzy membership layer used in this project. Suitable simulation models are available.

Fuzzy logic also has potential to complement remote sensing workflows, either by inclusion of remote sensing classifications within the framework (i.e. as additional layers of evidence), or within a remote sensing fuzzy logic framework to help decide spectral signatures that fall within the marginal range of classification. Many publications are available that describe similar applications for both scenarios.

4.6 Conclusion

The fuzzy logic method provides a conservative estimate of high producing grassland that is higher than existing LUM estimates but lower than LCDB4 estimates based on remote sensing. This we regard as a positive result, as the LUM classification is based on the now well-dated NZLRI dataset, and the LCDB4 has a potential to overestimate high producing grassland due to local growing conditions at time of image capture.

5 Report conclusions

- Definitions of high and low producing grassland are characterised as having criteria that are linguistically vague in both description and specification (e.g. 'low fertility', 'highly productive', typically, generally, mostly).
- Simulation modelling of annual pasture yield has potential as a method to differentiate high and low producing grassland. Several models are available for NZ grasslands. However, management and degree of land development are both major determinants of annual pasture yields. National datasets that adequately represent farm management and land development are unavailable for modelling (they do not exist).
- Fuzzy logic is an expert-guided weights of evidence method used widely in applications that have vague specification and/or imprecise data.
- Applied to the classification of managed grassland, the fuzzy logic approach provides a conservative estimate of high producing grassland that is higher than existing LUM estimates but lower than LCDB4 estimates based on remote sensing. This we regard as a positive result, as the LUM classification is based on the now well-dated NZLRI dataset, and the LCDB4 has a potential to overestimate high producing grassland due to local growing conditions at time of image capture.
- Improved quality and accessibility to national land use data would improve the fuzzy logic classification of high and low producing grasslands.

6 Recommendations

- That MfE consider the adoption of the fuzzy logic based classification of high and low producing grassland for the LUCAS LUM. It represents an improvement over known limitations of the current LUM and LCDB, and provides a conservative estimate based on previous classifications; environmental conditions for pasture growth; and land use type and intensity.
- That those involved with remote-sensing classification of NZ land covers consider using fuzzy logic within their grasslands spectral classification work flow, and/or provide a spectral-based 'degrees of truth' layer as an additional source of evidence for use in the fuzzy logic grasslands framework.
- That the New Zealand Government investigates the development of a comprehensive national land use mapping programme providing regular updates to the location and extent of different agricultural land uses across the country.

7 Acknowledgements

We are particularly grateful for the assistance of Michael Blaschek, Robbie Price, and Matteo Poggio for initial help with developing the fuzzy logic framework. Additional thanks go to Peter Newsome and David Pairman for help with definitions and underlying base layer inputs, and special thanks goes to Deborah Burgess for overall project guidance and patience. John Dymond is thanked for his critique and review.

8 References

Ausseil A-G, Medyckyj-Scott D, Ritchie A, Manderson A, Jolly B, Cooper J 2016. The Innovative Data Analysis research programme: an overview and progress to date. Soil Horizons newsletter, Issue 25. https://www.landcareresearch.co.nz/publications/newsletters/soil/issue-25/the-innovative-data-analysis-research-programme-an-overview-and-progress-to-date (accessed May 2018).

Barlow ND 1985. Value of sheep pasture, and the relationship between pasture production and stocking rate, New Zealand Journal of Experimental Agriculture 13 (1): 5–12.

Bedell RL 2000, GIS for the Geosciences: Short course volume. National Geological Society of America meeting, Reno, Nevada, November 2000.

Bretherton M, Scotter D, Horne D, Hedley M 2010. Towards an improved understanding of the soil water balance of sloping land under pasture. New Zealand Journal of Agricultural Research 53 (2): 175–185.

Cichota R, Vogeler I, Li FY, Beautrais J 2014. Deriving pasture growth patterns for Land Use Capability Classes in different regions of New Zealand. Proceedings of the New Zealand Grassland Association 76: 203–210.

Coolbaugh MF, Bedell R 2006. A simplification of weights of evidence using a density function, fuzzy distributions, and geothermal systems. In: Harris JR ed. GIS for the Earth Sciences, Geological Association of Canada, Special Publication 44, pp. 115–130.

Coop IE 1965. A review of the ewe-equivalent system. Journal of NZ Agricultural Science 1: 13–18.

Dark A, Birendra KC, Kashima A 2017. National irrigated land spatial dataset. Summary of methodology, assumptions and results. http://www.mfe.govt.nz/fresh-water/technical-guidance-and-guidelines/irrigated-land-new-zealand?_sm_au_=iVV7S6V8j88VDtMr (accessed May 2018).

Department of Conservation (DOC) 2018. DOC Public Conservation Areas (GIS data). https://koordinates.com/layer/754-doc-public-conservation-areas/ / (accessed June 2018).

Dodd MB, Barker DJ, Wedderburn ME 2003. Are there benefits of pasture species diversity in hill country. Proceedings of the NZ Grasslands Association 65: 127–132.

Gillingham A 1974. Influence of physical factors on pasture growth on hill country. Proceedings of the New Zealand Grassland Association 35: 77–85.

Greenwood PB, Paton RJ. 1985. Irrigation of a high-country Mackenzie soil. Proceedings of the New Zealand Grassland Association 46: 25–30.

Hicks D, Curran-Cournane F 2017. Matching Farm Production Data to Land Use Capability for Auckland. Technical Report 2017/020. Auckland, Auckland Council.

Hunter GG, Blaschke PM 1986. The NZ Land Resource Inventory Vegetation Cover Classification. Water and Soil Miscelleaneous Publication 101. Wellington, National Water and Soil Conservation Authority. 92 p.

Hutchinson GK, Richards K, Risk WH 2000. Aspects of accumulated heat patterns (growing degree-days) and pasture growth in Southland. Proceedings of the New Zealand Grassland Association 62: 81–85.

Kemp KK (Ed.) 2008. Encyclopaedia of Geographic Information Science. Thousand Oaks, CA, SAGE Publications.

Leathwick JR, Wilson G, Rutledge D, Wardle P, Morgan F, Johnston K, McLeod M, Kirkpatrick R 2002. Land environments of New Zealand. Auckland, New Zealand, David Bateman.

LIC (Livestock Improvement Corporation), DairyNZ. 2017. New Zealand Dairy Statistics 2016-17. https://www.dairynz.co.nz/media/5788533/nz-dairy-statistics-2016-17-web.pdf (accessed March 2018).

LINZ (Land Information New Zealand) 2010. Rating Valuations Rules 2008. LINZS30300. Version date: 1 October 2010. https://www.linz.govt.nz/regulatory/30300 (accessed June 2018).

Lynn I, Manderson A, Page M, Harmsworth G, Eyles G, Douglas G, Mackay A, Newsome P 2009. Land use capability survey handbook: a New Zealand handbook for the classification of land. Hamilton, Lincoln, Lower Hutt, AgResearch, Landcare Research New Zealand, Institute of Geological and Nuclear Sciences. 163 p.

Manderson A, Jolly B, Aussiel A-G 2018. The NZ Land Use Classifier. Landcare Research Contract Report LC3335.Lincoln, Manaaki Whenua – Landcare Research.

MfE (Ministry for the Environment) 2012. Land-Use and carbon analysis system: satellite imagery interpretation guide for land-use classes. 2nd edn. Wellington, Ministry for the Environment.

MfE (Ministry for the Environment) 2018. New Zealand's Greenhouse Gas Inventory 1990–2016. MFE Publication ME 1351. Wellington: Ministry for the Environment.

MfE (Ministry for the Environment) 2019. LUM 1990 2008 2012 v018 Data Description. https://data.mfe.govt.nz/layer/52375-lucas-nz-land-use-map-1990-2008-2012-v018/ (accessed January 2019).

Moir JL, Scotter DR, Hedley MJ, MacKay AD 2000. A climate-driven, soil fertility dependent, pasture production model. New Zealand Journal of Agricultural Research 43: 491–500.

Morton J, Gray M, Gillingham A 2005. Soil and pasture responses to lime on dry hill country in central Hawke's Bay, New Zealand. New Zealand Journal of Agricultural Research 48 (1): 143–150.

NWASCO (National Water and Soil Conservation Organisation) 1979. Our land resources: a bulletin to accompany New Zealand Land Resource Inventory worksheets / produced for the National Water and Soil Conservation Organisation by the Water and Soil Division, Ministry of Works and Development. Wellington, National Water and Soil Conservation Organisation.

Newsome P, Shepherd J, Pairman D, Belliss S, Manderson A 2018. Establishing New Zealand's LUCAS 2016 Land Use Map. Manaaki Whenua – Landcare Research Contract Report LC3369.

Newsome P 1992. New Zealand Land Resource Inventory Arc/Info Data Manual Edition 1, May 1992. DSIR Land Resources Technical Record 81. Lower Hutt, Department of Scientific and Industrial Research.

NWR (Nga Whenua Rahui) 2018. Legally protected areas by Nga Whenua Rahui. Spatial data set. https://www.arcgis.com/home/item.html?id=4376f7a733ca4598a3ed854185973348 (accessed June 2018).

Parker W 1998. Standardisation between livestock classes: the use and misuse of the stock unit system. Proceedings of the New Zealand Grassland Association 60: 243–248.

Phuong NH, Kreinovich V 2000. Fuzzy logic and its applications in medicine, International Journal of Medical Informatics 62 (2–3): 165–173.

QEII (Queen Elizabeth II National Trust) 2018. Queen Elizabeth II National Trust GIS data layer. Available by request: https://qeiinationaltrust.org.nz/publications-and-resources/gis-data/ (accessed June 2018).

Radcliffe JE, Cossens GG 1974. Seasonal distribution of pasture production in New Zealand. New Zealand Journal of Experimental Agriculture 2(4): 349–358.

Rogers G, Walker S, Lee B 2005. The role of disturbance in dryland New Zealand: past and present. Science for Conservation 258. Wellington, Department of Conservation.

Rutledge DT, Hoffmann N, Briggs C, Price R 2008. Protected Areas Network New Zealand (PAN-NZ): Metadata Database Survey and Needs Assessment. Landcare Research Contract Report LC0708/189. Hamilton, Manaaki Whenua Landcare Research.

Singh H, Gupta MM, Meitzler T, Hou Z-G, Garg KK, Solo AMG 2013. Real-life applications of fuzzy logic (Editorial). Advances in Fuzzy Systems – Special issue on Real-Life Applications of Fuzzy Logic 3: 1–5.

Statistics NZ 2018. Agricultural production statistics: June 2017 (final). https://www.stats.govt.nz/information-releases/agricultural-production-statistics-june-2017-final (accessed May 2018).

Suckling FET 1960, Productivity of pasture species on Hill Country, New Zealand Journal of Agricultural Research 3(3): 579–591.

Thompson S, Grüner I, Gapare N 2003. New Zealand Land Cover Database Version 2 Illustrated Guide to Target Classes. Wellington, Ministry for the Environment. https://lris.scinfo.org.nz/document/9322-illustrated-classes-lcdb2/ (accessed May 2018).

Trafford G, Trafford S 2011. Farm technical manual. Lincoln University, Lincoln.

Vogeler I, Cichota R, Beautrais J 2016. Linking Land Use Capability classes and APSIM to estimate pasture growth for regional land use planning, Soil Research 54: 94–110.

Zhang BS, Tillman R, Gillingham A, Gray M 2009. Fine-scale spatial modelling of pasture production and fertiliser responses under variable climate: assessing a decision support tool in pasture management. New Zealand Journal of Agricultural Research 52: 455–470.

Appendix 1 – Feasibility of modelling and thresholds review

Determining appropriate classes and threshold values for "high-" and "low-producing" grassland

Coby Hoogendoorn, Manaaki Whenua Landcare Research

Introduction

The Land Use and Carbon Analysis System (LUCAS) in New Zealand employs a land use map (LUM) to determine the effect of anthropogenic activity (land use and land use change) on net carbon C flux to the atmosphere. Grassland contributes 54% of the total land area of New Zealand (Inventory report 1990–2012; Table 7.1.2); with high producing (>10 t DM ha^{-1} yr^{-1}) grassland contributing 22% (~6 million ha) and low producing (< 10 t DM ha^{-1} yr^{-1}) grassland contributing 28% (~8 million ha). Distinguishing between these categories has important implications for estimating net C flux to the atmosphere as the two categories are assigned very different default values for the net amount of C fixed in above and below ground biomass: high producing grasslands have a net C fixed factor twice that of low producing grasslands (6.75 vs 3.05 t C ha^{-1} yr^{-1} for high- and low-producing grasslands, respectively). Additionally, the Tier 2 modelling approach used to estimate soil C (SC) stock change for the two classes of grassland relies on the above estimates of net C fixed in above and below ground biomass as a key variable to estimate SC stock for each grassland category.

According to the LUCAS description, high-producing grassland is defined as intensively managed pasture land of primarily high-fertility response grass species and low-producing grassland is defined by the assumption that indigenous and/or low-fertility response grass species predominate, and the land is hill land or areas of native tussock or low, shrubby vegetation, both above and below the tree line.

Aim

The aim of this brief review is to determine (1) whether the threshold values of < or > 10 t DM ha^{-1} yr^{-1} are appropriate classes and threshold values for high and low producing grassland (2) whether the current method for classifying grassland into low or high producing grassland adequately reflects realised levels of pasture production and (3) key information needed to assign grassland into the two categories to more accurately reflect true net C flux to the atmosphere.

Background

Carbon fixed by plants

Grassland plants fix atmospheric C through photosynthesis and while a large proportion of fixed C is rapidly respired, the net amount of C fixed is allocated to above and below ground biomass. Annual pasture production (and therefore net C fixed) is the net (growth–death) amount of herbage available for consumption by grazing animals and/or harvested for hay and silage. As a general rule, the greater the above ground biomass production, the greater the below ground biomass production (e.g. Saggar et al. (1999)), although relativities between above and below ground allocation of fixed C are affected by factors that affect the total amount of C fixed such as season (Saggar & Hedley 2001), soil fertility (Saggar et al. 1997), plant species identity (Saggar et al. 1997; Skinner et al. 2006; Rose et al. 2013), grazing intensity and grazing behaviour (Rose et al. 2013). Thus, management factors such as nutrient inputs, grazing system, and animal and plant species all interact and provide a complex and unpredictable dynamic between total amounts of C fixed, respired, and accumulated in above and below ground biomass, ultimately determining the amount and longevity of SC stocks.

Soil carbon (SC)

Carbon fixed during photosynthesis enters soil through root exudates, senescence of above and below ground plant tissue and dung excreted by grazing animals. In the majority of New Zealand soils the sole source of SC is organic matter. Soil organic matter consists of plant residues, root exudates, and micro and macro faunal residues, all at various stages of decomposition, cells and tissue of soil organisms and substances synthesized by soil microorganisms. Losses of SC occur through respiration by soil microbes, leaching of dissolved C and export of C in animal products (Hoogendoorn et al. 2011). The net balance between inputs and losses determine whether SC stocks increase, decrease or remain static over time, and is this balance is not easy to predict from first principles as demonstrated by Parsons et al. (2013) and McSherry and Ritchie (2013). In New Zealand, in general, low producing grassland has the highest SC stock, and stocks generally decrease as grassland transitions from being lower to higher producing as a result of single or multiple changes in management such as increased nutrient inputs, sowing of plant species with greater potential for biomass production, and increased utilisation of above ground biomass through increased stocking rates (Parsons et al. 2013, 2016). The impact of single or multiple management factors on SC storage will depend, amongst a variety of other factors, on geographic location, climate and soil type (McSherry & Ritchie 2013). The most recent review of data on the effect of management practices on SC stocks for New Zealand grasslands (Schipper et al, 2017) is inconclusive and points to the need for more detailed work on fundamental processes responsible for losses and gains, i.e. Parfitt et al. (1997) and Beare et al. (2014)) and longer term monitoring to capture real trends in SC stocks. Recent comprehensive modelling studies by Parsons et al. (2016) and Kirschbaum et al. (2017) illustrate the complexity in determining C balance of grazed grassland systems and the influence of different management practices and their interaction for predicting effects of management (nutrient input, plant genetics, stocking rate and stock type) on SC stocks.

In New Zealand, land use change from grassland to forest (plantation or indigenous) and back again is not uncommon. The impact of transitioning from forestry to pasture and the reverse has special consequences for net C flux to the atmosphere, and can be quite context specific (Guo & Gifford 2002; Kirschbaum et al. 2013; Kim & Kirschbaum 2015). However, in general, SC increases after land use change from forest (indigenous and plantation) to pasture and the reverse process usually decreases SC (Guo & Gifford 2002).

Estimating pasture production

In temperate regions such as New Zealand rainfall, soil temperature and solar radiation explain the majority of the variation in pasture production between and within regions (McAneney et al. 1982; McAneney & Judd 1983; Moir et al. 2000; McCall & Bishop-Hurley, 2003; Romera et al. 2009; Li et al. 2011). Thus, geographic location (latitude/longitude, altitude, and aspect) which governs rainfall (total annual and seasonal distribution), sunshine hours and air/soil temperatures and soil characteristics are key determinants of pasture production. Management attributes such as grazing frequency and intensity and nutrient inputs contribute strongly to realised potential; this was dramatically demonstrated for grassland in hill country by Suckling (1975), and later by Grant et al. (1981) and Lambert et al. (1983); (Lambert et al., 2014) and for lowland by Edmeades et al. (2006) and Moir et al. (2000). For example, Grant et al. (1981) demonstrated a more than doubling of average annual pasture production (16.3 cf. 7.5 t DM ha^{-1}) by adding nutrients (nitrogen and phosphorous) to an existing hill pasture with low soil fertility and dominated by low-fertility tolerant pasture species. Suckling (1975) was able to demonstrate substantial increases (up to 5 t ha^{-1}) in pasture production from lower North Island hill country with addition of essential nutrients, particularly phosphorous. Thus, inferences about pasture production based solely on geographic location may be misleading as nutrient addition and grazing management are a major contributor to realised pasture production (see especially Suckling (1975) and Lambert et al. (2014)). The longer-term impact of management intensity on pasture production is not always easy to predict; in reality, management factors that contribute to a grazing system being of low or high intensity occur in tandem and their effects on pasture production may not be additive (Parsons et al. 2016).

Inter-annual variability

The seasonal cycle of solar radiation reaching the earth's surface, and ambient temperature, differs little year by year, and this is the major driver of the seasonal pattern of pasture production. By contrast, mean monthly rainfall differs markedly between years. Consequently factors related to soil moisture usually explain the highest proportion of inter-annual variability in pasture production (Murray et al. 2007): for example, 60% of inter-annual variation in total annual pasture production of New Zealand pastures can be explained by variation in spring-summer total rainfalls (Moir et al. 2000).Thus, when estimating average annual pasture production it is particularly important to capture between year variation and this requires a multi-year measurement programme. In addition to impact of inter-annual variation in seasonal distribution of rainfall on pasture production, management and land use change such as pasture renewal (Tozer et al. 2015) or pasture establishment after deforestation (Hawke 2004; Elliott & Hawke 2007) often result in highly variable annual herbage production in the short term (less than 10 years), and may not reflect production over the long term (Parsons et al. 2011).

Surrogates for pasture production

In some situations, pasture quality (e.g. metabolisable energy and nitrogen content) is positively correlated to annual pasture production but there are a number of caveats to consider. One-off samples of herbage quality could act as a surrogate for pasture production only if herbage samples are taken at a time of year when plant phenology in combination with grazing management have the greatest impact on herbage quality and on annual pasture production. This is most likely the case in spring through to early summer when herbage with lower metabolisable energy and nitrogen content generally reflect the presence of plant species of lower nutritive value and/or a low stocking rate relative to the amount of DM available (i.e. low utilisation); each on their own or in combination may be indicative of low pasture production levels. However, information on this is scarce and most likely quite context specific (i.e. Earle et al. 2018).

Despite pasture being the sole feed supply for the majority of ruminants in New Zealand, high quality multi-year datasets of pasture production are scarce, and particularly so in recent decades. One particularly high quality and geographically comprehensive dataset of pasture production was collected during the 1940–80s (see Fig. 1 below) and this dataset has been used extensively in recent years to validate process-based models simulating pasture production for grazing systems research (e.g. Li et al. 2011; and White et al. 2008).

Of the 35 sites studied 43% could be classified as low producing and 57% high producing if the metric of focus is mean annual production. For this dataset, the average and median values for annual pasture production are not dissimilar (Appendix Table 1). However, it is noteworthy that despite 57% of sites being above the threshold of 10 t ha^{-1}, 88% of sites had at least one year when production was less than this threshold and 82% of sites had at least one year when production was greater than the threshold 10 t DM ha^{-1}, illustrating the importance of collecting long term information on pasture production for more accurate estimates of net C flux from grasslands.

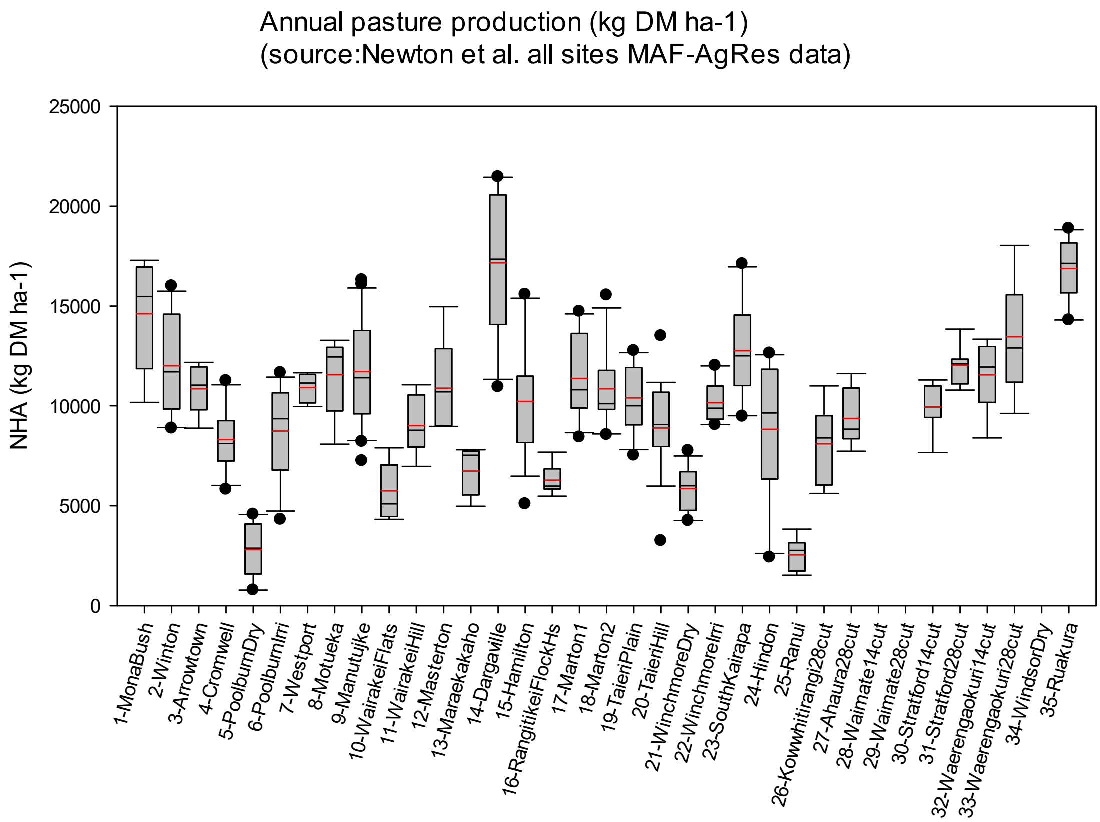


Figure: Annual pasture production for 35 sites across New Zealand (kg DM ha^{-1}). Boxes illustrate the 25th, 50th and 75th percentiles and whiskers denote the 5th and 95th percentiles; filled circles show outliers and red lines show the average for each site.

Over the past 2–3 decades there have been a number of studies simulating pasture production in New Zealand to explore the impact of: (i) farm management practices on primary production; (ii) climate change on primary production for the agricultural sector; and (iii) land use and land use change on C stocks (above and below ground). Simulation models of pasture production vary in complexity from predictive decision tree (Zhang et al. 2005, 2006, 2009; Zhang & Tillman 2007) and empirical (Moir et al. 2000; Edmeades et al. 2006; Romera et al. 2009) models to more complex process-based earth system models such as Biome-BGC model (Keller et al. 2014) and ORCHIDEE (Chang et al. 2016) and ultimately more spatially explicit process-based models such as APSIM (Li et al. 2011), HPM (Parsons et al. 2016) and CenW (Kirschbaum et al. 2017). Process-based modelling of grazing systems present unique challenges such as incorporating animal behaviour impacts on small-scale spatial heterogeneity of soil fertility, plant species composition and production (Snow et al. 2017). A recent meta-analysis of 38 international grassland studies (including one study each from New Zealand and Tasmania) related to plant productivity (above and below ground biomass accumulation) found management practices (namely nutrient inputs and grazing frequency and intensity) had approximately double the explanatory power for variation in plant biomass accumulation (above and below ground), compared with factors such as climate, which had a much smaller effect (Thebault et al. 2014). While the process-based models mentioned are well-validated for New Zealand grasslands and have the capability to predict C flux with some confidence and present a real possibility for application at national scale, they do require detailed input data and large computing capacity for application at the resolution required for national inventory purposes.

Summary

The existing LUCAS threshold for classifying grassland into two distinct categories (< or > 10 t DM ha^{-1}) at a national scale is reasonable based on current knowledge and best estimates of likely above and below ground biomass C fixed and SC stocks for low and high producing grassland. However, the current system for allocating grassland into these two categories is based solely on topography and assumes topography determines/or is correlated with the presence of either low or high producing pasture species. It assumes that high producing grassland is restricted to lowland areas, all lowland areas are intensively managed, and all contain improved pasture species. Additionally, it is assumed that all grassland in hill land is low producing and plant species of low production potential predominate. There is much evidence to the contrary; pasture production in hill land has been shown to respond positively to increased nutrient inputs and grazing intensity, and over time high fertility response plant species can predominate. Likewise, lowland grassland may be low producing if nutrient inputs are limited and grazing management extensive. Therefore, it is recommended that grassland be categorised into high or low producing based on the three criteria below:

(1) The most influential parameter influencing pasture production potential is geographic location which determines rainfall, temperature, solar radiation, soil type, altitude and aspect.

(2) Once geographic location is known, management factors that impact strongly on realised pasture production are nutrient inputs (especially N, P and lime) that ultimately determine soil fertility, and stocking rate which sets grazing frequency and intensity.

(3) Both animal and plant species identity may be helpful in refining estimates of pasture production further, but in and of themselves are not determinants. Inferences about pasture

production based solely on stock type (sheep & beef vs dairy) or grassland plant species mix may be misleading if not accompanied by information on nutrient inputs and stocking rate.

There is a lack of good quality, geographically diverse and multiyear datasets on pasture production post the early 1980s. Good quality multi-year datasets from geographic locations where grassland is a dominant land use would be ideal. In particular, multiyear datasets capturing inter-annual variation in pasture production could potentially be very important for estimating net C flux from grassland in a changing climate.

References

Chang JF, Ciais P, Herrero M, Havlik P, Campioli M, Zhang XZ, Bai YF, Viovy N, Joiner J, Wang XH, Peng SS, Yue C, Piao SL, Wang T, Hauglustaine DA, Soussana JF, Peregon A, Kosykh N, Mironycheva-Tokareva N 2016. Combining livestock production information in a process-based vegetation model to reconstruct the history of grassland management. Biogeosciences 13: 3757–3776.

Earle E, McHugh N, Boland TM, Creighton P 2018. Evaluation of the effects of ewe prolificacy potential and stocking rate on herbage production, utilization, quality and sward morphology in a temperate grazing system. Grass Forage Science 73: 247–256.

Edmeades DC, Metherell AK, Waller JE, Roberts AHC, Morton JD 2006. Defining the relationships between pasture production and soil P and the development of a dynamic P model for New Zealand pastures: a review of recent developments. New Zealand Journal of Agricultural Research 49: 207–222.

Elliott I, Hawke MF 2007. Best management practices for forestry to farming conversions. Proceedings of the New Zealand Grassland Association 69: 79–86.

Grant DA, Luscombe PC, Thomas VJ, 1981. Responses of ryegrass, browntop and an unimproved resident pasture in hill country, to nitrogen, phosphorus, and potassium fertilizers. 1. Pasture Production. New Zealand Journal of Experimental Agriculture 9: 227–236.

Guo LB, Gifford RM 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8: 345–360.

Hawke MF 2004. Conversion of forestry land back to productive pasture. Proceedings of the New Zealand Grassland Association 66: 157–162.

Hoogendoorn CJ, Bowatte S, Tillman RW 2011. Simple models of carbon and nitrogen cycling in New Zealand hill country pastures: exploring impacts of intensification on soil C and N pools. New Zealand Journal of Agricultural Research 54: 221–249.

Keller ED, Baisden WT, Timar L, Mullan B, Clark A 2014. Grassland production under global change scenarios for New Zealand pastoral agriculture. Geoscientific Model Development 7: 2359–2391.

Kim DG, Kirschbaum MUF 2015. The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates. Agriculture Ecosystems and Environment 208: 114–126.

Kirschbaum MUF, Saggar S, Tate KR, Thakur KP, Giltrap DL 2013. Quantifying the climate-change consequences of shifting land use between forest and agriculture. Science of the Total Environment 465: 314–324.

Kirschbaum MUF, Schipper LA, Mudge PL, Rutledge S, Puche NJB, Campbell DI 2017. The trade-offs between milk production and soil organic carbon storage in dairy systems under different management and environmental factors. Science of the Total Environment 577: 61–72.

Lambert MG, Clark DA, Grant DA, Costall DA, Fletcher RH 1983. Influence of fertiliser and grazing management on North Island moist hill country. 1. Herbage accumulation. New Zealand Journal of Agricultural Science 57: 149–164.

Lambert MG, Mackay AD, Ganesh S, Upsdell MP 2014. Responses of grazed New Zealand hill pastures to rates of superphosphate application. New Zealand Journal of Agricultural Science 57: 149–164.

Li FY, Snow VO, Holzworth DP 2011. Modelling the seasonal and geographical pattern of pasture production in New Zealand. New Zealand Journal of Agricultural Research 54: 331–352.

McAneney KJ, Judd MJ 1983. Pasture production and water-use measurements in the Central Waikato. New Zealand Journal of Agricultural Research 26: 7–13.

McAneney KJ, Judd MJ, Weeda WC 1982. Loss in monthly pasture production resulting from dryland conditions in the Waikato. New Zealand Journal of Agricultural Research 25: 151–156.

McCall DG, Bishop-Hurley GJ 2003. A pasture growth model for use in a whole-farm dairy production model. Agricultural Systems 76: 1183–1205.

McSherry ME, Ritchie ME 2013. Effects of grazing on grassland soil carbon: a global review. Global Change Biology 19: 1347–1357.

Moir JL, Scotter DR, Hedley MJ, MacKay AD 2000. A climate-driven, soil fertility dependent, pasture production model. New Zealand Journal of Agricultural Research 43: 491–500.

Murray RI, Yule IJ, Gillingham AG 2007. Developing variable rate application technology: modelling annual pasture production on hill country. New Zealand Journal of Agricultural Research 50: 41–52.

Parfitt RL, Theng BKG, Whitton JS, Shepherd TG 1997. Effects of clay minerals and land use on organic matter pools. Geoderma 75: 1–12.

Parsons AJ, Edwards GR, Newton PD, Chapman DF, Caradus JR, Rasmussen S, Rowarth JS 2011. Past lessons and future prospects: plant breeding for yield and persistence in cool-temperate pastures. Grass Forage Science 66: 153–172.

Parsons AJ, Thornley JHM, Newton PCD, Rasmussen S, Rowarth JS 2013. Soil carbon dynamics: The effects of nitrogen input, intake demand and off-take by animals. Science of the Total Environment 465: 205–215.

Parsons AJ, Thornley JHM, Rasmussen S, Rowarth JS 2016. Some clarification of the impacts of grassland intensification on food production, nitrogen release, greenhouse gas emissions and carbon sequestration: using the example of New Zealand. CAB Reviews 11: 1–19.

Romera AJ, McCall DG, Lee JM, Agnusdei MG 2009. Improving the McCall herbage growth model. New Zealand Journal of Agricultural Research 52: 477–494.

Rose L, Hertel D, Leuschner C 2013. Livestock-type effects on biomass and nitrogen partitioning in temperate pastures with different functional-group abundance. Grass Forage Science 68: 386–394.

Saggar S, Hedley C, Mackay AD 1997. Partitioning and translocation of photosynthetically fixed C-14 in grazed hill pastures. Biology and Fertility of Soils 25: 152–158.

Saggar S, Hedley CB 2001. Estimating seasonal and annual carbon inputs, and root decomposition rates in a temperate pasture following field C-14 pulse-labelling. Plant Soil 236: 91–103.

Saggar S, Mackay AD, Hedley CB 1999. Hill slope effects on the vertical fluxes of photosynthetically fixed C-14 in a grazed pasture. Australian Journal of Soil Research 37: 655–666.

Schipper LA, Mudge PL, Kirschbaum MUF, Hedley CB, Golubiewski NE, Smaill SJ, Kelliher FM 2017. A review of soil carbon change in New Zealand's grazed grasslands. New Zealand Journal of Agricultural Research 60: 93–118.

Skinner RH, Sanderson MA, Tracy BF, Dell CJ 2006. Above- and belowground productivity and soil carbon dynamics of pasture mixtures. Agronomy Journal 98: 320–326.

Snow VO, Cichota R, McAuliffe RJ, Hutchings NJ, Vejlin J 2017. Increasing the spatial scale of process-based agricultural systems models by representing heterogeneity: The case of urine patches in grazed pastures. Environmental Modelling and Software 90: 89–106.

Suckling FET 1975. Pasture management trials on unploughable hill country at Te Awa. III. results for 1959–69. New Zealand Journal of Experimental Agriculture 3.

Thebault A, Mariotte,P, Lortie CJ, MacDougall AS 2014. Land management trumps the effects of climate change and elevated CO2 on grassland functioning. Journal of Ecology 102: 896–904.

Tozer KN, Rennie GM, King WM, Mapp NR, Aalders LT, Bell NL, Wilson DJ, Cameron CA, Greenfield RM 2015. Pasture renewal on Bay of Plenty and Waikato dairy farms: impacts on pasture performance post-establishment. New Zealand Journal of Agricultural Research 58: 241–258.

White TA, Johnson IR., Snow VO 2008. Comparison of outputs of a biophysical simulation model for pasture growth and composition with measured data under dryland and irrigated conditions in New Zealand. Grass Forage Science 63: 339–349.

Zhang B, Tillman R 2007. A decision tree approach to modelling nitrogen fertiliser use efficiency in New Zealand pastures. Plant and Soil 301: 267–278.

Zhang BS, Tillman R, Gillingham A, Gray M 2009. Fine-scale spatial modelling of pasture production and fertiliser responses under variable climate: assessing a decision support tool in pasture management. New Zealand Journal of Agricultural Research 52: 455–470.

Zhang BS, Valentine I, Kemp P 2005. Modelling the productivity of naturalised pasture in the North Island, New Zealand: a decision tree approach. Ecological Modelling 186: 299–311.

Zhang BS, Valentine I, Kemp P, Lambert G 2006. Predictive modelling of hill-pasture productivity: integration of a decision tree and a geographical information system. Agricultural Systems 87: 1–17.